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USER SPACECRAFT CLOCK CALIBRATION SYSTEM (USCCS) USERS' GUIDE

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Section 1. USER SPACECRAFT CLOCK CALIBRATION SYSTEM (USCCS)

Introduction

This manual is dedicated to the measurement of time. Little data from any spacecraft is useful without knowledge of the time when it was gathered. Time can be used to relate data to events observed and to provide location by correlation with the orbit.

Logically, any vehicle could have a clock and call readings from this clock "TIME" however the scientific community as a body has designated Universal Time Coordinated (UTC) as the standard. UTC time, when used on the ground, is easily corrected for delays from the time standard's location. However, with the advent of orbital and free-flying spacecraft, the onboard spacecraft clock has become a virtual necessity. Due to variations in oscillator drift, the time extended from the spacecraft-clock, no matter how inherently accurate, can not be considered an absolute reference without some form of continuous comparison with UTC and the ability for updating. Global Positioning System (GPS) may become the timing standard for low earth orbiting satellites. However, until that time, the onboard clock will continue to be the primary standard. One caveat for potential users of GPS is the leap second problem[1]

The User Spacecraft Clock Calibration System (USCCS) is a method designed for calibrating the spacecraft clock with UTC to microsecond accuracy by using Tracking and Data Relay Satellite System (TDRSS) pseudo-random noise (PN) epochs. By measuring the time that a PN epoch leaves the White Sands Complex (WSC) and the time that it returns, the time that a particular PN epoch pulse arrived at the spacecraft can be determined (Figure 3-1). This time is measured in UTC since the ground station tags transmit and receive epoch times in UTC. The pulse arrival time at the spacecraft is approximately halfway between the ground transmitted and received time. The spacecraft clock time is recorded upon arrival of the PN epoch pulse, and is sent to the ground in the telemetry stream. The spacecraft clock can then be synchronized with UTC by comparing the spacecraft clock reading with the measured UTC time that was read. The current system guarantees accuracy of 5 μsec with respect to UTC and higher accuracy with respect to the ground terminal (GT) time standard.

This document is designed as a User's Guide to the USCCS. References are provided for more detailed definition. The following is an overview of the functionality of each section: Section 1 (this section) serves as an introduction to time and USCCS. Section 2 provides a statement of system accuracy while Section 3 discusses the requirements. A conceptual analysis of the USCCS is the basis of Section 4, which defines terminology, describes the physical principles involved and concludes with equation 12 to be implemented. System specifics are discussed in Section 5 where the method of error calculation in USCCS is defined. Error output is influenced by the course of

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[1] GPS uses an epoch time of January 6, 1980, 00:00:00 and has not accounted for the leap seconds that have been added since. There are currently 13 leap seconds unaccounted for as of this editing. This anomaly does not invalidate the use of GPS for marking seconds only for providing absolute time.

daily on-orbit operations, so ground terminal configurations affecting the volume and character of calculated error is also covered. Items unique to the Compton Gamma Ray Observatory (CGRO), the Consultative Committee for Space Data Systems (CCSDS) implementation in the Rossi X-Ray Timing Explorer (RXTE)/Tropical Rainfall Measuring Mission(TRMM) and the CCSDS implementation by the Earth Observing System Morning Crossing (TERRA) and EOS-PM are presented in Section 6. Finally, Section 7 discusses operational considerations.

Section 2. USCCS and RDD Accuracy

USCCS and RDD Accuracy

The USCCS technique uses TDRSS PN epochs where the time between epochs is stable to approximately 35 ηs. The UTC time of a PN epoch pulse is measured with a granularity of 200 ηs relative to the Ground Terminal (GT) cesium clock which is maintained within approximately 1μsec. of UTC at the Naval Observatory, (even though the general requirement for ground station accuracy is to within 5000 ηs (5 μsec.)). The recorded values are reported in the OPM-66. The GT clock is typically kept within l μsec. of the GPS. The GPS signal is known to be within 1 μsec. Thus the GT clock is known to within about 2 μsec. of UTC. An error log is kept at the GT, but absolute accuracy is limited to approximately 2 μsec because of the cumulative accuracy of the calibration references.

Prior to the USCCS, the return data delay (RDD) method, also known as Return Channel Time Delay (RCTD), was used to determine spacecraft clock error. This method is available as a backup to the USCCS and components of the RDD method are incorporated in the USCCS. The accuracy of the RDD method at the WSC is specified to be ±1/4 of a User data bit period or 3 μsec., whichever is greater. Accurate range data, which is inherent in the USCCS is required for, and was the weakest link in, the RDD method. In the past, the range data was obtained from NASA's Flight Dynamics Facility (FDF) or determined from vectors supplied by FDF. A simpler and more accurate method is recommended in Section 5. The less accurate RDD method is guaranteed to an accuracy of 5 μsec. at best, with respect to UTC.

 From a formal point of view, even though the USCCS technique involves time differences accurate to a few tens of nanoseconds, only 5 μsec. accuracy with respect to UTC is guaranteed because of the GT clock accuracy requirement and approximations that are often made in processing software.

Section 3. USCCS Components and Requirements

This section describes the six major components involved in the USCCS and their interfaces. The following subsections are organized by component. These subsections provide the USCCS requirements of each. Figure 3-1 shows an overview of system requirements and interfaces.

TDRS
RF EQUIPMENT
~1 µs DELAY

TYPICAL DISTANCE
GT - TDRS   40,000 Km
TDRS - USER   36,000 Km
USER - TDRS   36,000 Km
TDRS - WSGT   40,000 Km
d = 152,000 Km

$\mathbf{DT} = \dfrac{d}{t} = 0.5$ sec

$T_{PN} = 0.085$ sec

$\dfrac{\Delta T}{T_{PN}} = 5.8$ epoch periods

FWD LINK
(GT-TDRS)
S/C CMD
PN Range Code
~0.13 sec delay

RTN LINK
(TDRS-GT)
S/C TLM
PN Range Code
~0.13 sec delay

FWD LINK
(TDRS-S/C)
S/C CMD
PN Range Code
~0.13 sec delay

RTN LINK
(S/C-TDRS)
S/C TLM
PN Range Code
~0.13 sec delay

USER SPACECRAFT (SC)

CADH Configuration & Status
Spacecraft Time
Equipment Delay Estimates
Data Rate Dependent Delay
µs to ms

Time Tagged S/C telemetry
PN Epoch Transmission/
Return Times
Equipment Delay Estimates
GT Configuration
~1000 µs Data Delay
~1 µs RZS Delay SSA

WSC
STGT | WSGTU
Ground Terminal (GT)

TLM
TTM
OPM
ODM

NISN

GSFC
POCC
MSOC
TPOCC

S/C Commands
SHO Req
GCMRs

Figure 3-1. System Requirements and Overview

3.1 User Spacecraft Command and Data Handling (CADH) Subsystem

The spacecraft must have hardware to read the spacecraft clock upon receiving the PN epoch pulse and include that reading in the telemetry frame. If a full clock reading can be obtained and transmitted on command, it is sufficient to read only the fractional portion of the second upon receipt of the epoch.

For the RDD time correlation method, the User Spacecraft CADH Subsystem must associate a clock reading with a particular bit in the telemetry stream, for example, the first bit of each major frame. We call this the timing reference bit. The associated clock reading must be transmitted to the Project/Payload (Mission) Operations Control Center (POCC/MOCC[2]) in the telemetry frame.

A pulse supplied by the spacecraft transponder to the spacecraft-timing unit is required to indicate the arrival of a TDRSS range PN epoch at the spacecraft. This pulse, referred to as a Time Transfer Epoch, exists on the Second Generation and subsequent versions of the NASA Standard Transponder (Reference l) and is presented to the CADH module less than 100 ηs after arrival of the epoch. For both the RDD and USCCS time correlation methods, it is necessary to know the delay in the telemetry stream from the time the timing reference bit causes the spacecraft clock reading to the time that the timing reference bit reaches the spacecraft antenna. This delay must be measured prior to launch and is usually data rate dependent due to data clocking in the convolutional encoder and/or other coding circuits.

3.2 Tracking and Data Relay Satellite (TDRS)

No data unique to TDRS is required. The selected TDRS simply acts as a throughput device. Delays are defined in Section 4.4.2. The type of TDRS service does effect Ground Terminal Range Zero Set Delays (see Section 3.3)

3.3 White Sands Complex Ground Terminals (GT)

The GT must produce two sets of UTC time tags[3]:

1. The time of receipt of telemetry data bits 'Ground Receipt Time' (GRT) at the GT. This function is performed by NASA Integrated Services Network (NISN) for normal SN Users. EOS is using their own timing equipment (see section 6.3).

2. The time that a range epoch pulse is transmitted from the GT to the User spacecraft, t1, and the time that a range epoch pulse is received at the GT from the User spacecraft, t3. This information is passed from the WSC in an Operations Procedure Message (OPM-66) time transfer message, Reference 2. Appendix A shows the OPM-66 as sent from the WSC. The POCC will receive a slightly modified version from the Network Control Center (NCC) that also contains the User Support Identification Code (SUPIDEN), References 3 and 4.

Two sets of delay values are required from the ground terminal:

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[2] Note: POCC and MOCC are used interchangeably in this document. They both apply to the operations area for a particular spacecraft.
[3] One set of epoch times (forward and return) for USCCS and both epoch times and the GRT for RDD

1. Return Data Delay (RDD)[4]: The time required for telemetry data to travel from the receiving antenna to a point where it is time tagged by NISN. This delay is reported in an OPM-52 (Appendix B). It is translated into an OPM-62 in the NCC for transmission to the POCC. The component causing the largest portion of this delay (~98%) is the convolutional decoder. The delay is data rate dependent and on the order of milliseconds. For an S-band Single Access (SSA) service, the portion of the delay from the antenna to the receiver, reported in an OPM-66, is under a microsecond and can usually be ignored.

2. Range Zero Set (RZS): The forward Radio Frequency (RF) propagation delay from the forward Modulator Doppler Predictor (MDP) to the GT antenna and the return RF propagation delay from the GT antenna to the Integrated Receiver (IR). These values are referred to as RZS in this document and are reported in the OPM-66 where they are referred to as the forward and return PN time delay (Appendix A). The USCCS is based on the TDRSS ranging system, which is used to measure the RF propagation time from the GT antenna to a User spacecraft and back to the GT antenna. A spacecraft sitting on the antenna should result in a range measurement of zero. The RZS is subtracted from the raw measurement to yield the zero result.

3.3.1 GRGT/GUAM

The Guam Remote Ground Terminal (GRGT) does not currently support USCCS or RDD per NAM 370. OPM-66 is provided from GRGT if tracking is scheduled in the SHO and USCCS should be operational. Since GRGT is a full function SGLT, USCCS and RDD may be incorporated later.

3.4 NASA Integrated Services Network (NISN)

NISN time tags telemetry data in the Multiplexer/ Demultiplexer (MDM) unit as it builds 4800-bit NISN data blocks for transmission to Goddard Space Flight Center (GSFC) and Johnson Space Center (JSC). The first telemetry data bit of each block is time tagged with PB4 time, which is UTC, to a granularity of one microsecond and the accuracy of the GT time standard. This time is often referred to as the ground receipt time (GRT) or earth receipt time (ERT).

NISN blocks contain 4624 User data bits with the remaining 176 bits used for addressing, error detection and the PB4 time tag. NISN transports telemetry and message blocks to GSFC and makes the time tag available to the User. As projects migrate from the 4800 bit NISN block format to the Internet Protocol (IP) format a method to transmit the GRT of the timing reference bit or the information needed to calculate it must be developed. (See also Sections 3.5 and 5.1) Note: The current IP implementation done by NISN takes the user data (in 4800 bit blocks) and encapsulates it in IP packets. The packets are then sent using Unacknowledged Data Protocol (UDP) from WSC to GSFC.

Transition to full TCP/IP will necessitate finding a way to identify and timetag packets to perform the USCCS function. An investigation into this is currently ongoing.

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[4] USCCS does not rely on RDD except for initial calibration of the spacecraft clock.

3.5 Multi-Satellite Operations Control Center (MSOCC)

Since the OPM-52 and OPM-66 are sent from the ground terminal after termination of the pass, the RDD and USCCS analysis <u>can not</u> be performed in real time. Therefore, the Multi-Satellite Operations Control Center (MSOCC) must receive and store User telemetry data in block format in NISN blocks, and frame synchronize the data into Data Processing Services Subsystem (DPSS II) blocks. In producing these blocks, the MSOCC telemetry and command (TAC) computer uses the PB4 time tag from the NISN block to calculate and store a time tag for the first bit of each minor frame. These time tags represent the arrival time of the first bit of each minor frame at the GT MDM.

3.6 Transportable Payload Operations Control Center (TPOCC)

RXTE, TRMM and CGRO use the Transportable Payload Operations Control Center (TPOCC). There is generic software in TPOCC to deliver a GRT for each User frame. TPOCC does not contain generic USCCS software but does contain mission specific software. With the commonality of the TPOCC implementation, the changed specifics are minimal

3.7 Payload Operations Control Center (POCC)

The POCC must:

1. Have hardware and software to sort through the NISN blocks stored by MSOCC and select the relevant telemetry, OPM and TTM messages. The POCC must then determine which OPMs pertain to its service by searching for its SUPIDEN in the OPM.
2. Calculate the GRT of the telemetry reference bit if not done by MSOCC or TPOCC.
3. Accept and utilize processing control flags and constants.
4. Have software to calculate spacecraft clock difference from UTC and generate a report. A CGRO Clock Report is shown in Figure 3-2 and an RXTE Report is shown in Figure 3-3. RXTE software is provided as an example in Appendix D.

READING ON S/C CLOCK AT EPOCH	EPOCH AT S/C BASED ON WSC CLOCK	CLOCK ERROR	READING ON S/C CLOCK AT EPOCH	EPOCH BASED ON NGT CLOCK	CLOCK ERROR
75933314990.7	75933314992.4	-1.7	76035763415.2	76035763617.2	-1.9
75935357153.6	75935357155.4	-1.9	76037805785.2	76037805784.9	-1.7
75937399316.7	75937399318.4	-1.7	76039847950.9	76039847952.6	-1.7
75939536569.8	75939526571.7	-1.9	76041890119.1	76041890120.8	-1.7
75941568733.2	75941568734.8	-1.6	76043932287.1	76043932288.9	-1.8

Figure 3-2. CGRO Clock Error Report (USCCS Method)

T1 IN UTC	T3 IN UTC	T2 IN UTC	T2 CALC IN UTC	UTCF	I/Q	CLOCK DATA UTC-SC
SS:mmm:uu	SS:mmm:uu	SS:mmm:uu	SS:mmm:uu			(microsec)
39:143:306	39:669:379	39:406:345	39:406:342	986712	x	-3
44:163:579	44:689:652	44:426:617	44:426:615	986712	x	-2
54:289:213	54:815:286	54:552:251	54:552:249	986712	x	-2
59:309:486	59:835:559	59:572:524	59:572:522	986712	x	-2
09:435:120	09:961:193	09:698:159	09:698:156	986712	x	-3

Figure 3-3. RXTE Clock Error Report[5]

3.8 EOS Data and Operations System (EDOS)

The morning crossing (ascending mission) Earth Observing System satellite (TERRA) will use the USCCS. The current plan is that the EOS Data and Operations System (EDOS) will handle the GRT tagging and receive the information normally found in the OPM-66. This is further detailed in section 6.3

3.9 International Space Station Interim Control Module (ISS ICM)

The ISS ICM uses USCCS. The data is being sent through the IP transition MDMs. These MDMs annotate the data with Ground Receipt Time prior to IP encapsulation.

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[5] This is only a representation since the clock report is printed in landscape mode with very small fonts. The number of characters was limited in this edition. Actual printout would also include year and DOY on each item.

Section 4. Analytical Considerations (Concepts)

4.1 TDRSS Spacecraft Ranging

The TDRSS uses 84 different PN codes in spacecraft ranging. Each TDRSS User is assigned a unique PN code. The PN code is a digital pattern that modulates the RF carrier along with the digital User data allowing several Users to operate simultaneously on the same carrier frequency. PN coding is used on all Multiple Access (MA) services. PN Coding is also used on Single Access (SA) services at data rates less than 300 kbps. The PN pattern rate is approximately 3 Mbps; thus each User data bit is broken into 10 or more pieces called chips.

The length of all PN codes used for ranging is: $(2^{10} - 1) \times 256 = 261{,}888$ chips

The PN code rate ($RATE_{PN}$) and return carrier frequency (F_{RTN}) are a function of the forward carrier frequency (F_{FWD}) calculated from the following:

$$\text{MA, SSA} \qquad RATE_{PN} = \left(\frac{31}{221 \times 96}\right) \times F_{FWD} \qquad F_{RTN} = \left(\frac{240}{221}\right) \times F_{FWD} \qquad (1)$$

$$\text{KSA} \qquad RATE_{PN} = \left(\frac{31}{1469 \times 96}\right) \times F_{FWD} \qquad F_{RTN} = \left(\frac{1600}{1469}\right) \times F_{FWD} \qquad (2)$$

For example, with an MA or SSA forward frequency of 2106.406250 MHz, the PN chip rate is 3.077799479 MHz or 325 ηs per chip. The PN code repeats itself every 261,888 chips; thus, at the above PN chip rate, the period of the PN code is given by the following:

$$T_{PN} = PN\,Period = \frac{261888\,chips}{3077799.479\,chips/sec} = 0.08508936394 \text{ Sec.} \qquad (3)$$

This number is frequently rounded and referred to as 85 milliseconds in conversation. The forward PN frequency is an integral function of the forward carrier frequency so that only a single phase locked loop is required in the transponder for both carrier and PN tracking. The rising or falling edge of a PN code chip is stable to about $\pm$ 30 ηs.

In every PN, code there is a sequence of eighteen consecutive digital ones. This portion of the pattern is called the PN epoch. Since the example PN code period is 0.085089364 seconds, a PN epoch is generated every 0.085089364 seconds, the same as the period of the code. As the PN epoch portion of the PN code is generated and applied to the forward link, a time tag is also generated and held temporarily in the MDP (Figure 4-1). The User spacecraft also generates a PN code in its transponder and synchronizes it with the incoming (forward) code. Thus, upon receipt of the forward PN epoch, the User spacecraft simultaneously generates and transmits a return PN epoch. The return PN code is different from the forward PN code, but the epochs are synchronized
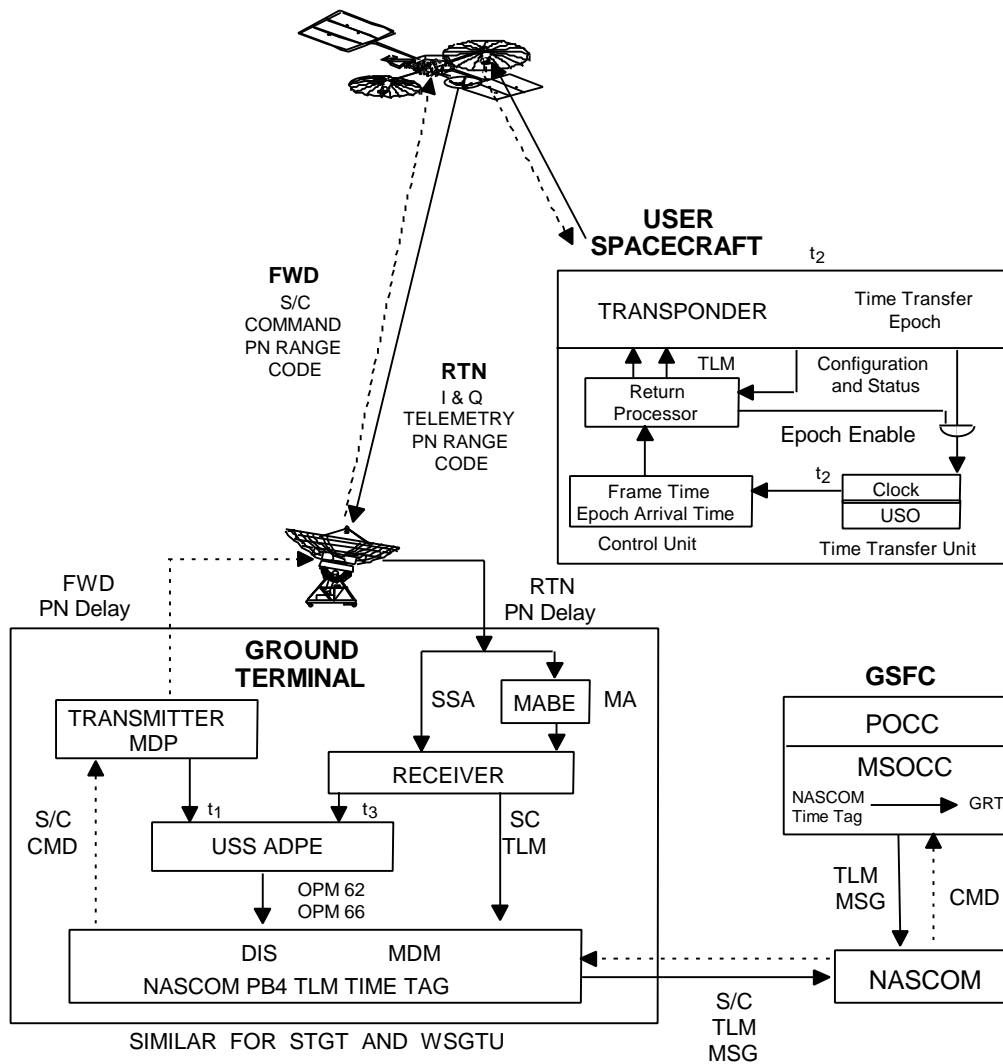
Figure 4-1. USCCS Data And Message Flow

When the White Sands Complex (WSC) IR receives the return PN epoch in the return PN code, a time tag is sent to the MDP, which then sends both forward and return time tags to the User Services Subsystem (USS) Automated Data Processing Equipment (ADPE). Since the round trip travel time is about 0.5 seconds (see Figure 3-1), and the epoch pulses are approximately 0.085 seconds apart, the time tag for the return epoch and the time tag for the forward epoch do not correspond to the same PN epoch. The forward epoch that was just time-tagged will arrive back at the ground more than six epoch periods later. Transmission time from the GT through the TDRS to the User spacecraft and back is equal to the difference between the forward and return time tags, range delay (which is roughly equivalent to six epoch periods), minus ground communications equipment delay (RZS), TDRS forward and return delays, and User spacecraft transponder delays. This time is used by the Flight Dynamics Facility (FDF) to determine one-way User spacecraft range to approximately $\pm$ 10 meters which is then used for User orbit determination. System accuracy is required to be <35 ηs (10.5 meters). TDRSS ranging is used on a daily basis and is constantly calibrated and checked. The location of NASA spacecraft is known at all times and the ground terminals routinely point antennas and communicate with

TDRS attesting to the system accuracy and dependability. The fact that the ranging system accuracy is far greater than that required for spacecraft clock correlation should lend confidence to the USCCS procedure.

4.2 USCCS Clock Calibration Overview

The PN epochs used in spacecraft ranging are also used in the USCCS. When a PN epoch is transmitted from WSC, it is time tagged in units of UTC (t1) by the MDP. When the PN epoch arrives at the User spacecraft (t2, unknown), the User spacecraft simultaneously generates and transmits a corresponding return epoch. The return epoch is then received at the GT where it is time tagged in units of UTC (t3). These time tags are generated by the WSC atomic clock. Details on using t1 and t3 to find t2 are given later, but fundamentally to about 1 μsec accuracy

$$t2 = \frac{t1+t3}{2} \tag{4}$$

When the PN epoch arrives at the User spacecraft, a pulse from the transponder called a "time transfer epoch" is sent to the spacecraft timing unit to trigger a clock reading. This spacecraft clock time is returned to the ground terminal in the spacecraft telemetry data and compared to the UTC time that the spacecraft clock was read, t2; hence, clock calibration.

Times t1 and t3 are reported to the POCC from the WSC in the OPM-66.[6] The basic clock calibration algorithm uses the fact that the RF signal travel times from WSC through the TDRS to the User spacecraft and from the User spacecraft through the TDRS back to WSC are the same to within l μsec. The epoch arrives at the User spacecraft at a time approximately halfway between t1 and t3, (Equation 4).

A rigorous analysis, Appendix C, shows that Equation 4 is accurate to within 1 μsec. for the SSA service. The remainder of Section 4 describes sub-microsecond improvement in accuracy and terms that must be included to obtain an Equation similar to Equation 4 that will be correct to 1 μsec. accuracy for both MA and SSA services. MA is different from SSA due to TDRSS equipment delays (see Section 4.4). The reader not interested in these corrections may skip to Section 5.

 Every 85 ms a new epoch is transmitted from the ground terminal so a new set of t1, t2, t3 are generated. In this document, t1, t2, t3 will be used to represent the UTC times of arbitrary epochs pulses, not necessarily a set that is used for clock correlation (see Figure 4-2). In Section 5, a method of correlating a given set of t1, t2, t3 is described and the notation is changed to t_1, t_2, and t_3 when referring to a particular epoch that triggered a spacecraft clock reading.

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[6] Note that the delta times reported in OPM-66 (Appendix A) are time offset from the one-second time mark for forward and return epochs. The Forward Delta Time reflects the time delta between the first forward epoch and the time mark. Similarly, the Return Delta Time reflects the time delta between the time mark and the first return epoch after the first forward epoch. Ref. 11 STGT Phase II specification 5-157:5.2.3.2.3.c.1 and Ref. 12 530-RSD-WSC: 5-138:5.3.3.2.c.1

Sub-microsecond corrections related to Doppler and equipment delays are considered in Section 4.3 and 4.4, and a more detailed Equation for the time that the spacecraft clock is read, t2, is presented there.
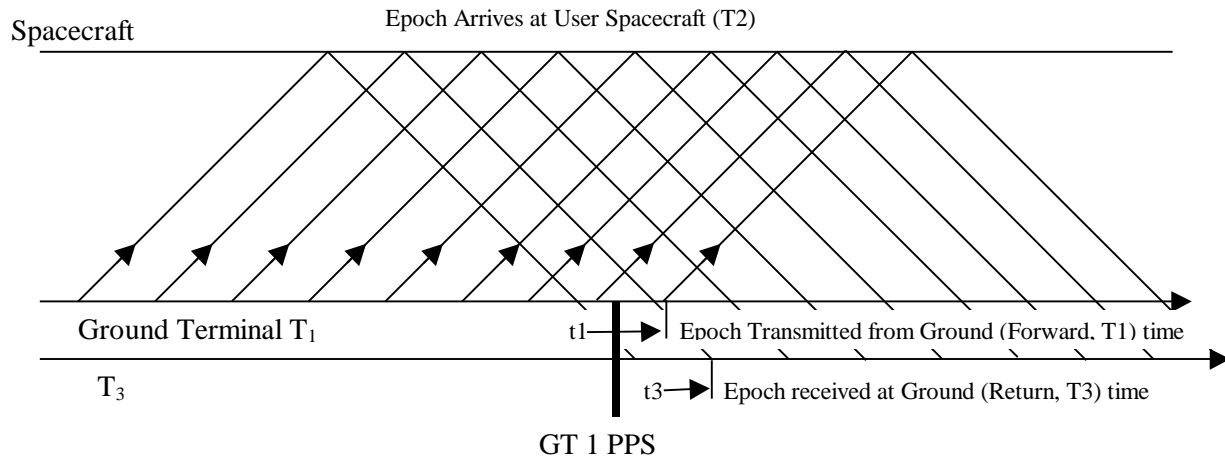
Figure 4-2. Forward/Return Epoch Timeline

4.3 Motion Corrections

The forward and return signal travel times are not exactly equal because of motion and equipment delays. Each of these can be further broken down by TDRS, User spacecraft and ground terminal. A rigorous analysis of the motion effects is presented in Appendix C.

4.3.1 Motion

For a low earth orbiting (LEO) User, the spacecraft velocity is of the order of 10^4 meters per second. The time between receipt and transmission of the PN epochs by the User spacecraft is about 0.5 μsec. for a NASA transponder; thus, the spacecraft will have moved 10^4 m/sec x 0.5 μsec. = 0.005 meters, or 0.5 cm between receipt and transmission of an epoch. This movement results in less than a one-nanosecond difference (0.5 cm ~ 0.017 ηs) between the forward and return signal travel times and can effectively be ignored.

The TDRS orbital velocity is about 3 x 10^3 m/sec. The signal travel time from TDRS to User and back to TDRS is about 1/4 second. The GT is moving at about 1600 m/sec, and there is approximately 0.5 sec between transmission and receipt of the forward and return signal at the GT. After considering the orbital geometry for a low earth orbiting satellite, Appendix C, one finds that, at worst, this would cause a 0.9 μsec. difference between forward and return signal travel times, $t_F - t_R$. The correction required to Equation 4 is $(t_F - t_R)/2$ resulting in:

$$t2 = \frac{t1 + t3}{2} + \frac{t_F - t_R}{2} \tag{5}$$

When accuracy no better than a few microseconds is required, User, TDRSS and GT motion error may generally be ignored. Often, software utilities used in POCC software limit the USCCS

calculations so they can not produce accuracy better than about 1 μsec. (see also Section 2.0). For example, TPOCC software uses the UNIX timevalue structure, which maintains six digits of microseconds in integer format causing calculations to quickly lose significance in the least significant digit. This results from rounding to the nearest 1 μsec after operations generating fractional μsec. While writing the RXTE USCCS software, we kept the calculations in floating point until the last step to keep this error to a minimum.

4.3.2 Doppler

The motion considerations in Section 4.3.1 cover the fundamental principles that cause the Doppler effect. Doppler carrier frequency and PN frequency shift cause no timing errors.

In order to accurately determine t2 from the ground measured values t1 and t3, it is necessary to know the exact rotational motion of the TDRS, the User and the GT. The difference between the forward and return travel time is then determined and results in the value of t2. When the actual motion and various velocities are not available, it is common to use variations of periodic events (the Doppler effect) to infer the velocities and relative orbital positions. From the position in orbit, the correction to t2 is determined. Doppler is combined with geometric consideration in Appendix C to obtain the sub-microsecond correction indicated by $(t_f - t_r)/2$ in Equation 5.

4.4 Equipment Delay Corrections

The forward and return equipment delays are not the same and the MA return equipment delay is about 54 μsec. greater than the SSA return equipment delay. Since these delays are known values, adjustments can be made for them. The resulting Equation is essentially Equation 4 with equipment delay corrections.

First, the parameters involved in a TDRS range measurement will be evaluated. At WSC the range value is obtained from the difference between t1 and t3 to which five or six return epoch periods must be added and then that quantity divided by two. We will call this MEASURED. The MEASURED range is defined to be from the ground terminal antenna to the spacecraft antenna. Starting at the transmitter in Figure 4-1 the signal path delay components yield the following:

$$
\begin{aligned}
\text{MEASURED} \quad =& \text{GT}_{\text{FWD transmitter to antenna delay}} + t_{\text{ GT to TDRS}} + \text{TDRS}_{\text{FWD delay}} \\
& + t_{\text{ TDRS to User}} + \text{SC}_{\text{ FWD transponder delay}} + \text{SC}_{\text{ RTN transponder delay}} \\
& + t_{\text{ User to TDRS}} + \text{TDRS}_{\text{ RTN delay}} + t_{\text{ TDRS to GT}} + \text{GT}_{\text{ RTN antenna to receiver delay}} \qquad (6)
\end{aligned}
$$

Equation 6 contains four space propagation delays 't' and six equipment delays. The equipment delays are referred to as RZS and are subtracted from the measured value to obtain the range. These equipment delays and a few others must be accounted for in the USCCS calculation of t2 if maximum accuracy is desired. Delays in the forward ground equipment (starting at the MDP), the forward TDRS delay and the User transponder forward delay, may be added together and used as one value in the calculations, as can the return transponder, TDRS and ground equipment delays.

$$t_{\text{FWD eqp}} = GT_{\text{FWD transmitter to antenna delay}} + TDRS_{\text{FWD delay}} + SC_{\text{FWD transponder delay}}$$

$$t_{\text{RTN eqp}} = SC_{\text{RTN transponder delay}} + TDRS_{\text{RTN delay}} + GT_{\text{RTN antenna to receiver delay}} \tag{7}$$

The forward delays can then be added to t1 to get an effective t1 ($t1_{\text{eff}}$), and the return delays can be subtracted from t3 to get an effective t3 ($t3_{\text{eff}}$).

$$t1_{\text{eff}} = t1 + t_{\text{FWDeqp}}$$

$$t3_{\text{eff}} = t3 - t_{\text{RTNeqp}} \tag{8}$$

Using these corrections in equation 5, the time of arrival of the epoch at the spacecraft is then given by the following:

$$
\begin{aligned}
t2 &= \frac{t1_{\text{eff}} + t3_{\text{eff}}}{2} + \frac{t_F - t_R}{2} \\
&= \frac{\left(t1 + t_{\text{FWD eqp}}\right) + \left(t3 - t_{\text{RTN eqp}}\right)}{2} + \frac{t_F - t_R}{2} \\
&= \frac{t1 + t3}{2} + \frac{t_F - t_R}{2} + \frac{t_{\text{FWD eqp}} - t_{\text{RTN eqp}}}{2}
\end{aligned} \tag{9}
$$

The above Equation for t2 is the UTC time that the epoch pulse characterized by a particular t1 and t3 arrived at the PN correlator in the User Transponder. The last delay that must be accounted for is the time required for the Time Transfer Epoch pulse that is emitted from the transponder to cause the User spacecraft CADH module to read the spacecraft clock. We refer to this delay as T_{User}, (or T_{latch}). Finally, the time that the clock was read based on ground UTC time is given by the following:

$$t_2 = \frac{t_1 + t_3}{2} + \frac{t_F - t_R}{2} + \frac{t_{\text{FWD eqp}} - t_{\text{RTN eqp}}}{2} + T_{\text{User}} \tag{10}$$

The last step is to write equation 10 in terms of the ground station (forward and return) PN delays[7], which are reported in the OPM-66, and the TDRS PN delays where

$$RZS_{\text{FWD}} = \text{Forward PN delay} + TDRS_{\text{FWD delay}}$$

$$RZS_{\text{RTN}} = \text{Return PN delay} + TDRS_{\text{RTN delay}} \tag{11}$$

Using Equations 7, 10, and 11:

---

[7] Ref Appendix A - OPM-66 Time Transfer Message Format: Data Item 8 (Fwd) and Data Item 9 (Return)

$$t_2 = \frac{t_1 + t_3}{2} + \frac{t_F - t_R}{2} + \frac{RZS_{FWD} - RZS_{RTN}}{2}$$

$$+ \frac{SC_{FWDtransponderdelay} - SC_{RTNtransponderdelay}}{2} + T_{User_{USCCS}} \qquad (12)$$

where:

t_2	UTC time SC clock is read
t_1, t_3	measured
t_F - t_R	difference between forward and return signal travel time, less than 1 μsec. for a LEO satellite.
$SC_{transponder}$	Table 1
RZS_{FWD}, RZS_{RTN}	OPM 66, Table 4-3, Equation 11
$T_{UserUSCCS}$	Delay from arrival of epoch in transponder until SC clock is read

CGRO requires only 10 μsec. accuracy, so these corrections may all be ignored or an average value, about -0.5 μsec., may be used. Prior to the acceptance of the USCCS by the TDRSS Networks Test Branch, Code 533, it was found that if all corrections including atomic clock calibrations are made, the technique as implemented is accurate to ± 0.6 μsec. The difference between the WSC and GSFC atomic clocks is thought to be the dominant error factor.

The delay values used are shown in Tables 4-1 & 4-2 and are further described below.

Table 4-1. Typical Spacecraft Delays for CGRO

$SC_{FWD\ transponder\ delay}$	.080 μsec.
$SC_{RTN\ transponder\ delay}$	.246 μsec.
$T_{User\ USCCS}$	.142 μsec.
$T_{User\ RDD}$	117.800 μsec.

Table 4-2. Typical Ground Terminal RZS Delays for the WSC

$t_{transmitter\ to\ antenna\ (FWD)}$	0.7 μsec.
$t_{antenna\ to\ receiver\ (RTN)}$	
SSA	0.8 μsec.
MA	55.5 μsec.

For STGT and WSGTU these values are found in the OPM-66.

4.4.1 User Spacecraft

The transponder delays, which are part of the forward and return equipment delays, are explicitly shown in Equation 12. Typical values for a second generation NASA standard transponder are

given in Table 4-1. The forward and return values stated are the average of the CGRO A and B transponder.

Once an epoch is correlated in the transponder, it will typically take 20 ηs for the time transfer epoch pulse to appear at the output connector of the transponder. This pulse is the signal for the CADH system to record the spacecraft clock time. The time between the generation of this pulse to the time that the CADH system actually records the spacecraft clock time is called T_{latch} alternatively it is called T_{user}. The circuit on CGRO will latches the reading on the pseudo PB5 clock at the next tick of the 4096 kHz oscillator, which occurs somewhere in the next 244 ηs. Thus, T_{latch}/T_{User} averages 142 ηs. It is incumbent on the spacecraft CADH designer to make this value as static as possible, because T_{latch}/T_{User} ultimately affects the accuracy of the USCCS determination.

There is another CADH delay, which is not part of the epoch or ranging delay but is required in the RDD calculation of Section 5.1. As telemetry is being created in the CADH, the first bit of the major frame triggers the reading of the spacecraft clock separate from the reading caused by the epoch. Because of the internal delays, the clock is actually read some time after this telemetry timing reference bit is created. There is also a delay between the creation of the telemetry reference bit and its reaching the antenna. Correlating the clock reading with the telemetry requires the net of these delays, which will be several bit periods long because of data clocking. This net delay is called the User spacecraft return data delay, $T_{User\ RDD}$, and its value for CGRO (Reference 5) is given in Table 4-1. The transponder delay contribution to Equation 12 is less than 1 μsec.

4.4.2 TDRS

The TDRS delays are part of the forward and return RZS as used by the FDF but they are not included in the OPM-66 so they must be handled separately. They are similar from one vehicle to another for a given service. For TDRS 1 through 7, the following values are typical:

Table 4-3 TDRS Delays (Typical)

	SSA	MA
Forward	250 ηs	207 ηs
Return	308 ηs	1133 ηs[8]

4.4.3 Ground Terminal

TDRSS range measurements are from the range reference point on the ground antenna to the spacecraft antenna. In this Section, discussion centers on the ground station RF propagation delay that is referred to as the RZS. This is the net delay from when the epoch is created in the MDP until it reaches the GT antenna, plus the delay from when a return epoch is received in the GT antenna until it reaches the IR. The RZS values will be found in the OPM-66 where the terminology used is "Forward (Return) PN time delay".

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[8] Surface Acoustic Wave (SAW) filters are used in TDRS for processing the MA signal. The SAW filters introduce the additional delay over SSA. Their contribution in Equation 12 amounts to less than 1 μsec.

4.4.3.1 SSA

When the greatest possible accuracy is required, the User must obtain the forward and return RZS values for his pass and apply the correct values. When accuracy better than 1 or 2 μsec. is not required, an average value may be used or, for SSA, the corrections may be ignored completely. Using Tables 4-1 and 4-2, Section 4.4.2 and Equation 12, for the SSA case, yields the following:

$$t2 \cong \frac{t_1 + t_3}{2} + \frac{t_F - t_R}{2} - 0.02 \, ms \tag{13}$$

4.4.3.2 MA

The MA beam forming equipment (MABE) at the WSC uses a digital rather than an analog implementation. Because of data clocking when handling a signal in the digital form, the propagation delay through the MA return equipment has a significant delay, about 55 μsec. This delay, is part of the return RZS or PN delay, and is reported in OPM-66. Due to the size of this delay, the correction can not be ignored but an average can be used when accuracy better than 1 or 2 μsec. is not needed. For MA:

$$t2 \cong \frac{t_1 + t_3}{2} + \frac{t_F - t_R}{2} - 27.35 \, ms \tag{14}$$

Since the t_1 and t_3 in equations (13) and (14) must be obtained from data in the OPM-66, it is recommended that Equation 12 be used. Equation (12) will result in correct calculation for either SSA or MA. The following description is simply to indicate the size of the ground terminal correction terms.

4.5 SOC/RF SOC

For testing with the Simulations Operations Center (SOC)/RF SOC, the T_{User} delay includes the time required for the signal to go from the transponder at the RF SOC to the spacecraft simulator and timing equipment at the SOC. When originally tested with the CGRO simulator, $T_{User} = 2.765$ μsec. The typical transponder delays given in Table 4-l may be used for a SOC test.

4.6 Doppler Compensation Enabled/Inhibited

The techniques as described in this paper work properly when Doppler compensation at WSC is enabled (DCE) and when Doppler compensation is inhibited (DCI). Under DCE conditions, the frequency of both the carrier and PN pattern is adjusted at the ground transmitter so that the User receives his nominal frequencies. The USCCS error reports will show a constant value (over a 10 minutes pass) for the clock error as expected. When Doppler compensation is inhibited, as is common for the tracking portion of the service, the clock error reports will also show the same constant value for clock error. A close examination will show that DCI, the forward frequency is fixed and the forward epoch period will remain constant. In either case, DCE or DCI, the USCCS will work correctly.

 Originally, the CGRO USCCS error reports showed a drift in the clock error of approximately 50 ηs/sec during DCI, which was caused by their onboard data system placing the clock data in the

telemetry one frame late. This was corrected in the POCC software by simply retrieving the data for a given frame, from the following frame. Since the required data is placed in both minor frame 31 and 63 and minor frame 63 contained the correct data for a given frame, using minor frame 63 was an alternate workaround for CGRO

SECTION 5. THE USCCS ALGORITHM

The problem at this point is to decide which of the many epochs leaving the ground and returning to the ground cause a particular clock reading on board the spacecraft. We must distinguish a t_1, t_3 pair, which yields the high accuracy associated with the USCCS. In Section 6 we will examine details that differ among the various Users. Here we will use as an example, a spacecraft at an altitude of 450 km and other parameters as indicated in Figure 5-1.

TDRS E at 41.0		
r_{TDRS}	=	42164.2 Km
h_{GRO}	=	450 Km
$r_{e_{AV}}$	=	6378.2 Km
r	=	6379.6 Km
r_{WSGTU*}	=	-1539.4 Km
x_{WSGTU*}	=	-5160.9 Km
y_{WSGTU*}	=	3408.1 Km
*WSGTU - Central Antenna		

One Way Range		
R_{MIN}	=	75,723 Km, .252585 sec
R_{MAX}	=	84,504 Km, .281875 sec

WSGTU
106.8° W Longitude
32.5° N Latitude

TYPICAL
TDRSS h is ± 15 km
GRO h is ± 60 km
R_{WT} is ± 400 km

Figure 5-1. Maximum/Minimum Range to User

The difference between the maximum range to the User (84,500 km.) and the minimum range (75,700 km) is such that the round trip signal travel time never differs by more than one epoch period; 0.563750 sec - 0.505170 sec = 0.058580 sec < 0.085 sec. Various spacecraft altitudes are

considered in Section 5.1 and it can be seen that differences of 0.059 sec maximum and 0.505 sec minimum are typical. To determine which return epoch t_3 is the result of a particular forward epoch t_1, it is a simple matter of adding the minimum round trip range time (0.505 sec) to t_1 and then searching for the first t_3 after that time. Once a particular t_1, t_3 pair is found, the exact range propagation time can be found to within about 1μsec. for SSA the round trip propagation time is: $t_{\text{Round Trip Range}_{ssa}} = t_3 - t_1$ and the one way range time is one half of this. For MA where the large MABE delay of 55 μsec. comes before the T_3, time tag, the round trip time is $t_{\text{range}} = t_3 - t_1 - 55 \mu\text{sec.}$ The one way range time is half of this value.

These range delays are valid at a time half way between t_1 and t_3. The range delay naturally falls out of the t_1 and t_3 times made available in the OPM-66 and we will make use of this information in resolving which t_1, t_3 pair caused a particular space clock reading at t_2.

In the next section, we discuss the RDD method of clock correction before continuing with the USCCS.

5.1 Return Data Delay

A byproduct of the USCCS's use of various forward and return range epoch pairs is the ability to accurately determine the range to the spacecraft at a given time. Accurate knowledge of the spacecraft range allows one to calculate the return data delay from the spacecraft. Coupled with the GRT, the RDD method is a valid clock calibration method in its own right and is assumed available as a backup to the USCCS. For both methods there is a point in the telemetry used as a time reference (the telemetry timing reference bit) and both methods require that a reading of the spacecraft clock be made at some known time relative to that bit. For this discussion, the first bit of the telemetry frame will be used as that point. At the WSC, the MDM at the Data Interface System (DIS) accepts the received serial telemetry data stream and formsec.4800-bit NISN blocks containing 4624 data bits and a header and trailer. The header of each block contains the ground arrival UTC time (to microsecond accuracy, PB4) of the first data bit in that block. Software at the MSOCC or TPOCC examines the blocks to find the first bit of the spacecraft telemetry frame. From the GRT of the first data bit of the NASCOM block, the telemetry data rate and the position of the first spacecraft telemetry major frame bit in the NASCOM block, the UTC ground arrival time of the major frame first bit or telemetry reference bit, can be determined. In the following, the ground terminal atomic clock is referred to as UTC.

Ground arrival time of first bit of frame (GRT) =

> PB4 of 1st data bit of NASCOM block +

> (bit count from 1st data bit of NASCOM block to1st bit of frame) x   (16)
>   (telemetry bit period)

For CGRO and the Hubble Space Telescope (HST), this calculation is done by the TAC and the POCC is supplied with the GRT of the first bit of each frame.

The ground arrival time of the first data bit of the major frame is used to determine the UTC time when the first bit triggered a spacecraft clock reading, according to the following formula:

Time first bit of major frame caused spacecraft clock reading =

$$\text{GRT -RZS}_{rtn}\text{-Range- T}_{tdrs}\text{-Tuser}_{rdd} \tag{17}$$

Where:

GRT = ground arrival time of first data bit of frame (in UTC)

RZS_{rtn} = delay of ground terminal equipment (obtained from OPM-62)

Range = range propagation delay (variable, obtained via direct measurement from OPM-66 or via indirect ephemeris calculation, approx. 0.266 sec.)

T_{tdrs} = delay through TDRS (approx. 1 μsec. for all spacecraft # 1-7)

Tuser_{rdd} = User spacecraft internal telemetry delay (User spacecraft return data delay average of A and B Transponder, Remote Interface Unit (RIU), Pre Multiplexing Processor (PMP), and coding delay for CGRO is 117.8 μsec.).

A comparison between the UTC value determined from the above formula and the spacecraft clock reading of the major frame first bit time reported in the spacecraft telemetry data will yield the spacecraft clock error. CGRO identifies this procedure as the Telemetry Interface Method, while the generic TDRSS term for it is the RDD method or RCTD. For the WSC, the RDD method is specified to be accurate to 1/4 of a data bit period for data rates less than 100 Kbps. For data rates between 100 Kbps and 2 Mbps, the specified accuracy is ±3 μsec. Above 2 Mbps there is no MDM time tagging hence, no GRT of the return data, so the RDD method cannot be used. In general, clock correlation is done at data rates between 4 Kbps and 32 Kbps, with the higher data rates providing greater accuracy. At 32 Kbps, the bit period is 31.25 μsec.; thus, this should be sufficient for ±10 μsec. requirement. In practice, delays that are smaller than the accuracy of the method are ignored, i.e., TDRS, User transponder and ground terminal RF propagation delay. Data re-clocking delays must not be omitted from RDD calculations.

The largest factor in the RDD calculation is the range propagation delay, and the calculation is extremely sensitive to the value used. For a given spacecraft transmission time, the range value used typically must be valid for within about 1 second of that time in order to obtain the above stated accuracy. Under worst case conditions, the relative velocity between a LEO User and TDRS will be about 7.6 Km/sec. In order that the range error contribute less than 10 μsec. to the clock calibration error, the range value must be correct within 3000 m or within 0.4 sec. It is recommended that all Users request the OPM-66 and obtain their range delay from this direct measurement. Other less accurate and more complicated methods include an in house ephemeris calculation or use of FDF predicted range.

The ground terminal delay is supplied in the OPM-62 (Appendix B) which should be used in a POCC's operational software, but the values for STGT and WSGTU are stable and may be calculated from:

$$\text{GT Delay }_{SSA} = 103.8 \text{ T}_b + 6 \text{ μsec.}$$

$$\text{GT Delay }_{MA} = 102.8 \text{ T}_b + 60 \text{ μsec.}$$

The following table is based on these formulas.

Table 5-1. STGT/WSGTU Delay for Various Data Rates

TLM Data Rate	4 kbps	8 kbps	16 kbps	32 kbps
SSA	25956 µsec.	12981 µsec.	6494 µsec.	3250 µsec.
MA	25760 µsec.	12910 µsec.	6485 µsec.	3273 µsec.

The one way range travel time variation for a User at an altitude of 450 Km is 29 msec. An RDD User who is willing to use an average range delay can perform a clock calibration to an accuracy of about 15 msec. using only the GRT. The extreme range and range propagation times in terms of a Users altitude, h, are shown in Figure 5-1 and Table 5-2 and are given by:

$$R = R_{\text{WSC-TDRS}} + R_{\text{TDRS-User}}$$

$$R_{\text{MIN}} = R_{\text{WSC-TDRS}} + R_{\text{TDRS orbit}} - (R_{\text{earth}} + h)$$

$$R_{\text{MAX}} = R_{\text{WSC-TDRS}} + R_{\text{TE}} + R_{\text{EU}}$$

$$T_{\text{MIN}} = R/C \text{ (speed of light)}$$

Where:

$$R_{\text{WSC-TDRS}} = 40386 \text{ km}$$

$$R_{\text{TDRS orbit}} = 42162 \text{ km}$$

$$R_{\text{earth}} = 6378 \text{ km}$$

Table 5-2. Altitude vs. Delays

h km	R_{MIN} km	T_{MIN} 1 way	T_{MIN} 2 way	R_{MAX} km	T_{MAX} 1 way	T_{MAX} 2 way	T_{avg} km	DT 1 way	DT 2 way
400	75770	.2528	.5056	84357	.2814	.5628	.2671	.0286	.0572
450	75720	.2526	.5052	84501	.2819	.5638	.2673	.0293	.0586
600	75570	.2521	.5042	84894	.2832	.5664	.2677	.0311	.0622
800	75370	.2515	.5030	85356	.2848	.5696	.2681	.0333	.0666

For most Users, the spacecraft delay is less than a millisecond. Several examples are given in Table 5-3.

Table 5-3. Spacecraft Delay

User *	Data Rate	T_b	T_{SCRDD}		One Half Bit Reference Shift	Total
		(µsec.)	Nb	(µsec.)	(µsec.)	(µsec.)
CGRO	32 kbps	31.25	3.77	117.8	1/2 T_b = 15.6	133.4
HST	4 kbps	250	~200	~5000	1/2 T_b = 125.0	
	32 kbps	31.25	~0	<1000	1/2 T_b = 15.6	
UARS					1/2 T_b =	
EUVE					1/2 T_b =	
XTE**	32 kbps	31.25	18.25	570.3	1/2 T_b = 15.6	589.5
TRMM	32 kbps				1/2 T_b =	
EOS**	16 kbps	62.5	16384+1+…	1024000+	1/2 T_b = 31.25	
	1 kbps	1000	2048+1+…	2048000+	1/2 T_b = 500	
TOPEX	16 kbps		2.99	186.88	1/2 T_b = 31.25	218.17

    *   all spacecraft include convolutional coding.

    **   also includes Reed-Solomon coding

The spacecraft delay required for clock calibration is actually the difference between two delays. Basically it is the time from the creation of the timing reference bit, until that bit is transmitted from the spacecraft antenna. More specifically it is the above time interval minus the time from creation of the time reference bit until the clock is read. For example, if the internal circuits delay the clock reading for a time equal to the time it takes for the timing reference bit to reach the antenna, then the spacecraft delay is zero; the timing reference bit leaves the spacecraft at the same time that the clock is being read.

Table 5-4 TERRA Spacecraft Clock Calibration Time Delay Data

Time Delay Source	Comments	Latency (msec.)	Variability (msec)
Fwd: Transponder Delay	HGA →SBT2	0.4448	<TBD> depends on antenna and SBT in use
Rtn: Transponder Delay	SBT2 →HGA	.463	<TBD> depends on antenna and SBT in use
Transponder PN Epoch turn around	Receipt at xpdr to Pulse out to antenna	1.2775	<.00113
Transponder PN Epoch Pulse to CTIU	Receipt at xpdr to Pulse out to CTIU	<TBD>	<TBD>
Transponder downlink delay 16 kbps (worst case)	GN Modes	140.97	<(-0.0313)
	TDRSS modes	63.22	<(-0.0313)
Transponder downlink delay 1 kbps (worst case)	GN Modes	225.03	<(0.0313)
	TDRSS Modes	1000.72	<(0.0313)
CTIU Epoch sampling	Receipt →Timetag	<.05	0.0 - 1.5
CDHS delay: 16 kbps	1_{st} bit of CADU with respect to Major Cycle pulse	93.77	None
CDHS delay: 1 kbps	1_{st} bit of CADU with respect to Major Cycle pulse	1500.02	None
CDHS delay: 16 kbps	HK packet timestamp with respect to start of Packet Transmission	1.024E6	None
CDHS delay: 1 kbps	H&S packet timestamp with respect to start of Packet Transmission	2.048E6	None

CADU	Channel Access Data Unit
CDHS	Command and Data Handling Subsystem
CTIU	Command and Telemetry Interface Unit
GN	Ground Network
HGA	High Gain Antenna
HK	Housekeeping telemetry
H&S	Health and Safety telemetry
SBT2	S-band Transponder #2
TDRSS	Tracking and Data Relay Satellite System

5.2 USCCS Forward Epoch Time (t_1) Determination

In this section and the next, it is assumed that the range delay from the ground terminal to the User is known. The intent is to use appropriate t_1, t_3 pairs, as described earlier in Section 5.

Our goal is to determine which t_1, t_3 pair triggered a spacecraft clock reading at t_2, which is then reported in the telemetry. Only one in 20 to about one in 100 epochs stimulate a clock reading.

Some spacecraft event allows the next epoch that arrives to cause a clock reading. We will assume that the event is the beginning of a telemetry frame or a Virtual Channel Data Unit (VCDU) (See Section 6 for spacecraft specific details). Starting with the GRT of the frame that enabled the clock reading, an RDD calculation is done to determine when the telemetry frame in question was created on the spacecraft. The range delay is then subtracted from this time. The resultant UTC time is the earliest possible time an epoch could have left the ground and then triggered a spacecraft clock reading. The desired t_1 is the first one found with a value greater than that time just calculated.

Since several t1, t3 pairs have been pre-calculated from the OPM-66 TTM, the exact time of the forward epoch, t1, corresponding to a given telemetry frame is then determined and Equation 12 is used for the final calculation of t2.

A refinement that will avoid an occasional miscorrelation of epochs makes use of the clock reading at the beginning of frame (or telemetry reference bit) and the clock reading that occurred when the epoch arrived. By adding this delta time to the earliest possible time an epoch could have left the ground, a more accurate estimate of t_1 is obtained.

CGRO, RXTE, and TRMM make a full clock reading at the telemetry reference bit but only report the sub-second portion of time for the epoch arrival. Since the epoch must occur within 0.085 sec, of being enabled, there will be no ambiguity. When the sub-second portion of the telemetry reference time is greater than 0.915 sec, the epoch sub-second portion may be less than 0.85 sec. This indicates roll over to the next second and must be handled in the software.

5.3 USCCS Return Epoch Time (t_3) Determination

For a LEO satellite the t_1, t_3 pairs are determined by using a known minimum range delay. Once a particular t_1 is determined, the associated t_3 is the first one occurring after about 0.5 second beyond that t_1. See Section 5.1 for more detail.

5.4 Calculation of Spacecraft Epoch Arrival Time in UTC

Approximately halfway between the forward epoch ground departure time, t_1 and the return epoch ground arrival time, t_3, is the time that the epoch was at the spacecraft and triggered a clock reading, t_2. Use Equation 12 of Section 4 for accuracy. This calculated value of t_2 must be after the spacecraft epoch enable time, but not by more than 85 msec. If not, there is an error in the data and this set of t_1, t_2, and t_3 should be discarded.

This calculation began with the GRT of a particular major frame. The t_2 calculated above is compared with the clock reading associated with that frame for clock correlation.

Once a spacecraft clock is set, it is extremely unlikely that it will drift by even one msec.before the next calibration. Since epoch pulses are 85 ms. apart, subsequent calibrations can ignore the RDD preliminaries and simply calculate a t_2 for each of the t_1, t_3 pair using Equation 12. The clock errors will then be the difference between the epoch arrival time found in the telemetry and the nearest t_2 found above. Operationally, it would be most logical to run an RDD pass with the WSC complex to ascertain the general clock error. This error could then be used to jam or reset the clock. The next pass should then be used for another RDD session to verify the reset has been properly implemented. From that point on, running the USCCS would be suitable since the clock should be within one epoch period of real time.

5.5 Decoding the OPM-66

To reduce the message load only the first forward epoch and first return epoch after the first forward PN epoch is time tagged at STGT or WSGTU each second. These are referred to as Forward (Return) Delta Time in the OPM-66. Because the PN period is approximately 85 ms, this amounts to one of every eleven or twelve and occasionally thirteen PN epochs (only on the return). Using the reported epochs, the others can be interpolated to determine at what time they left the ground or returned to the ground. For example, suppose the forward epoch transmit times (t1s) at the modulator were (hours, minutes omitted, only seconds shown; actual values contain seven figures after the decimal point):

3.960, **4.045**, 4.130, 4.215, 4.300, 4.385, 4.470, 4.555, 4.640, 4.725, 4.810, 4.895, 4.980, **5.065**

The time transfer message would contain only 0.045 (t_1') for second 4 and 0.065 (t_1') for second 5. POCC software must interpolate to determine all of the other times during second 4 after first calculating the exact PN period for that second from:

$$T_{PN} = \frac{t1(j+1) - t1(j)}{N} \qquad \begin{array}{l} \text{where N} = 11, 12 \text{ and} \\ \text{occasionally 13 on t3}^9 \text{ only.} \end{array} \qquad (18)$$

In the above example, t1 (j + 1) = 5.065, t1(j) = 4.045 and N = 12. The Doppler effect causes the epoch period to vary around the nominal value of 0.085 sec by less than ±1 msec.. N is determined by choosing a value and checking that the result is between 0.084 and 0.086 sec. The day of year and seconds of the day information is reported in the PB1 time format in the OPM-66.

---

[9] The occasional 13 in the return comes from the implementation of T1, T3 reporting at WSC wherein T1 is the first after the second mark while the T3 is the first after the first T1 after the second mark. The only time this shows up is as a vehicle is going away from TDRS and the first T3 is decreasing and subsequently becomes less than T1. In all cases, the PN period falls between 84 and 86 msec.

Alternatively, the number of PN epochs can be computed by comparing the difference between the two values with the following table where the .084 and .086 values were used.

Table 5-5. Epoch Repetition Rate MIN-MAX

N	Min	Max
11	0.924	0.946
12	1.008	1.032
13	1.092	1.118

Following determination of N, equation 18 can be implemented directly which will provide the period of an epoch. The intervening epochs are then determined by repetitively adding the epoch period to the preceding epoch time

The structure is the same for the t3s. Interpolation for a particular forward (or return) epoch must be based on the two surrounding measured (reported) forward (or return) epochs only. This is because the PN period varies during the orbit due to the Doppler effect and because the forward and return contribution to the Doppler can be different. For example, during the Doppler compensation inhibited (DCI) mode, which is often used during a tracking service, the forward PN period, is constant but not equal to 0.085089 sec. At the same time, the return PN period will change from second to second. In making the T_{PN} calculation, equation 18 is used except that N can be 11, 12 or 13. Note that the 13 will be only an occasional entry where 12 and 11 are routine.

Section 6. Spacecraft Specific Details

6.1 Compton Gamma Ray Observatory (CGRO)

6.1.1 Clock and Data Handling Structure

CGRO uses a fixed major frame and minor frame structure, not in the CCSDS format. A major frame contains 64 minor frames, each of which contains 1024 bits. During normal operations, the data rate is 32 kbps, resulting in a major frame rate of one every 2.048 seconds. The on board clock is in UTC format rather than simply a counter. CGRO refers to their clock as a PB5 although it differs slightly from the NASA PB5 time format. PB5 is composed of:

Julian Day	Second of Day	Milliseconds	Microseconds	Nanoseconds
14 bits	17 bits	10 bits	10 bits	10 bits

On the CGRO spacecraft, the epoch reading is inhibited until 16 ms after the beginning of the major frame. Thus the clock reading caused by the epoch is from 16 ms to 16 ms + 85 ms = 101 ms after creation of the first bit of the major frame. The difference between these two times, is referred to as D2B by CGRO. D2B is an accurate measure (to a fraction of a microsecond) of the difference in time between the epoch arrival and the first bit of the frame, even if the clock is considerably off from UTC. Equation 17 gives the UTC time that the first bit of the frame was created based on RDD. D2B is now added to that time to get the time an epoch arrived at the spacecraft in units of ground UTC and is accurate to about 10 μsec.

The oscillator, driving the clock, is an ultra-stable oscillator (USO) running at 4.096 MHz and has a frequency range of 1 Hz controlled with 12 bit granularity. Hence, there is control at roughly 6×10^{-11}, which is about 5 μs per day. Caution must be used when extracting clock readings from CGRO telemetry. Both the telemetry reference time and the epoch time are placed into minor frame 31 and minor frame 63. Due to on-board latencies, the clock data does not get placed into the required buffers in time for minor frame 31 to be updated prior to transmission. Thus, minor frame 31 contains the clock readings from the previous major frame. Minor frame 63 contains clock data from the current frame.

6.1.2 CGRO Conversion From Spacecraft 4.096 MHz Oscillator to PB5

The ultra stable oscillator in the CGRO spacecraft is set to a frequency of 4096 kHz. Thus, 4096 ticks of this clock are exactly one millisecond. Conversion from oscillator ticks to the PB5 time format is simple for the millisecond and higher units but requires a conversion factor for the microsecond and nanosecond portion. The 4096 counts that make a millisecond require 12 bits. The ten most significant bits are pseudo microsecond bits and the least significant 2 bits are pseudo-nanosecond bits. Of the pseudo-microsecond bits each count, which is 4 ticks of the 4096

kHz clock, is 1/1024 of a millisecond or .9765625 μsec. The 10-bit pseudo-microsecond count must be multiplied by .9765625 to obtain the microsecond portion of the PB5 time.

The 2-bit pseudo-nanosecond portion of the count may be thought of as the two most significant bits of a four-bit count, where the two least significant bits are always zero.

CGRO has no requirement to specifically distinguish nanoseconds, so the time is most easily dealt with by dividing the full 12-bit sub-millisecond count by 4096. The result, kept in decimal format and rounded to two places, will give the time in microsecond and hundredths of a microsecond.

6.2 Rossi X-Ray Timing Explorer/ Tropical Rainfall Measuring Mission (RXTE/TRMM)

6.2.1 Clock and Data Handling Structure

RXTE and TRMM use very similar data systems. RXTE is used in the following description but the following also applies to TRMM.

RXTE uses Consultative Committee for Space Data Systems (CCSDS) internationally recommended frame packing and coding structure. This involves Reed-Solomon (RS) coding, Virtual Channels (VC) and instrument packets within a given VC that are referred to by their application identification (APID) number. See Reference 9.

The use of the CCSDS frame multiplexing process caused RXTE designers to trigger a clock reading based on a frame that is already constructed (VCDU) and is on its way to the transponder. On the leading edge of the 32-bit frame synchronization marker of each VC0 frame whose sequence number is evenly divisible by 16, (Modulo 16), a timing trigger pulse is generated. This pulse causes the hardware to latch a current clock reading. The full 64 bit clock reading and the VC0 frame count value that triggered the reading is sent to the data system for processing. In addition, the time transfer epoch (or all ones epoch) circuit from the transponder is armed. When the next TDRSS range epoch arrives, the subsecond portion of the spacecraft clock is again latched and this value is sent to the data system.

From the CCSDS point of view, the clock is treated as an instrument and a 112 byte APID1 packet on VC0 is constructed. It contains the VC0 sequence number of the frame that triggered the clock readings, the two clock readings (referred to as the telemetry synch time and the all 1s epoch time), the UTC correction factor (UTCF), plus other information, see Figure 6-1.
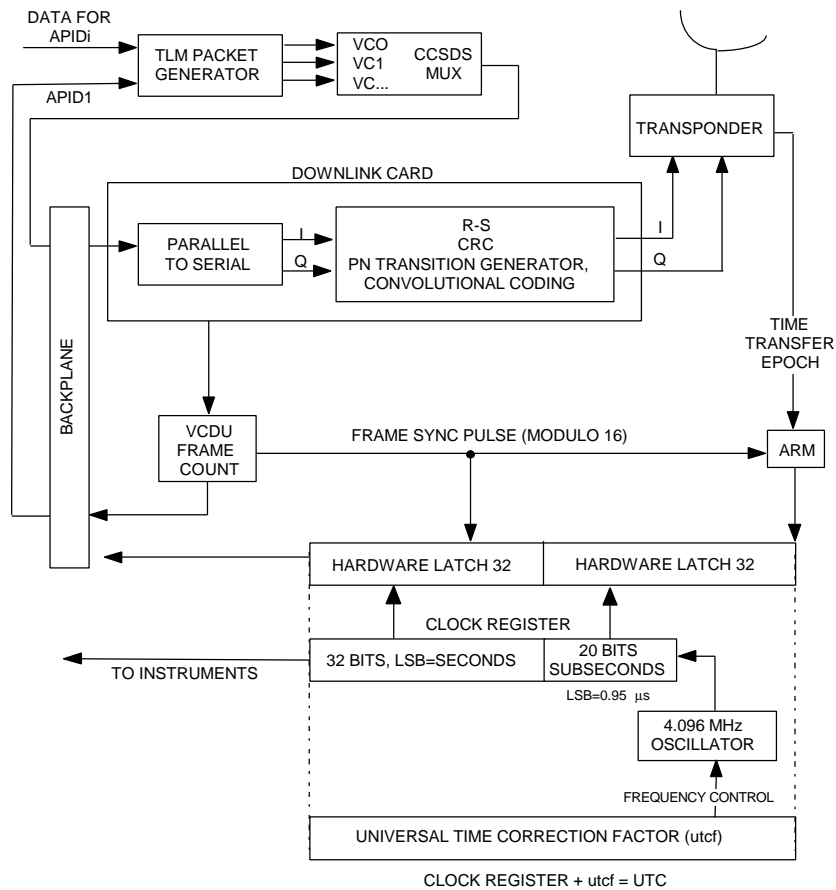
Figure 6-1. XTE/TRMM Implementation of USCCS Signals and CCSDS Packets and Frames

The arrival of the VC0-APID1 on the ground is not time critical. The progress of the VC0 that instigated the APID1 is. Since this VC0 is already formed and is in no way altered by the spacecraft data system other than the RS and Convolutional encoding and RF modulation which has a fixed and measured time delay, its time of creation can be calculated. Using the GRT of the leading edge of the first bit of the frame synchronization marker and an RDD type of calculation, the UTC time of on board timing trigger pulse is determined.

The RXTE telemetry frame is composed of 5 RS codewords each containing 252 bytes, plus a 32 bit synchronization marker for a total of 252 x 8 x 5 + 32 = 10112 bits. Since only every 16th frame is used for timing at 32 kbps, a correlation frame and associated APID1 is generated every (16x10112 bits)/(32000 bits/sec) = 5.056 sec. Under other conditions, the APID1 is sent to the ground even less often. The RXTE software is written to wait for an OPM-66, which is sent at the end of a tracking service, before it begins processing APID1 data.

6.2.2 Rossi X-Ray Timing Explorer Conversion from Binary to Mission Elapsed Time

The RXTE APID1 packet that contains the clock readings is not in a simple binary (or hex) form. Several time fields, for example the telemetry synchronization time and the utcf, are stored as 32 bits of seconds and 32 bits of subseconds. The seconds portion is simply a binary (or hex) number that is easily converted to decimal number of seconds, but the subseconds portion must be calculated if the spacecraft is using a 2^{32} Hz oscillator. For the telemetry synchronization time and the epoch field, 5 hex characters or 20 bits of the 32-bit field are used. To convert these values to microseconds, the binary value must be divided by 2^{20}.

For example 0FED 1000(hex) represents

$$\frac{0FED\,1(hex)}{2^{20}} = \frac{65233(decimal)}{2^{20}} = 0.062\,211 \text{ sec.}$$

The UTCF uses all 32 bits of the subsecond portion, hence it must be divided by 2^{32} when all 32 bits are carried. For example 3825 3727(hex) represents

$$\frac{3825\,3727(hex)}{2^{32}} = \frac{941\,963\,047}{2^{32}} = .219\,317\,862 \text{ sec.}$$

The all 1's epoch subsecond field is reported with an additional confusion; the two 16 bit words making up the 32-bit field are reversed. For example 5000 1D9F(hex) represents

$$\frac{1D9F\,5000(hex)}{2^{32}} = \frac{1D9F\,5(hex)}{2^{20}} = \frac{121\,333}{2^{20}} = .115\,712 \text{ sec.}$$

These 32 bit fields must be declared in a "C" language type statement as unsigned long to allow correct interpretation.

6.2.3 Mission Operations Control Center Software

See Appendix D

6. 3 Earth Observing System (EOS)/TERRA

When CCSDS is used as the telemetry format, spacecraft clock correlation can become complicated. The implementation used in the TERRA spacecraft makes the clock correlation relatively easy. Two possible problems that can arise when following the CCSDS recommendations are related to variable packet length and R-S coding delay. Both of these potential problems have been eliminated by using a fixed packet length and a fixed delay greater than that necessary to build the CADU, which includes the R-S coding delay.

In the housekeeping 16 kbps mode, a major cycle is 1.024000 seconds long during which time 16384 bits are transmitted. The unit transmitted, which is referred to as a packet, is contained in eight CADUs, hence, each CADU contains 2048 bits (256 bytes or octets). Each CADU is a single shortened R-S code word (252 octets) plus a frame marker (four octets). There is no R-S interleaving.

A packet begins its creation on one major cycle pulse, buts its transmission does not begin until the following major cycle 1.024000 seconds later.

Two pieces of information are required for both USCCS and RDD clock correlation. The time of the timing reference bit (first bit of first of eight CADUs that contain an EOS packet), and the time that a TDRS range epoch was received. In this spacecraft, all timing and bit clocking is derived from the 4.000 MHz master oscillator (MO). The MO is divided down to create 8.000 millisecond minor cycles while 128 of these minor cycles create the 1.024-second major cycle. The MO also runs the on-board clock, which displays in Julian time: days since 1958, milliseconds of day and microseconds. When a major cycle starts, the Command Telemetry Interface Unit (CTIU) prepares for the next PN epoch pulse. On arrival of that PN epoch pulse, the CTIU reads the s/c clock and inserts it into the telemetry stream. The time that the reading was made is also recorded as number of minor cycles (8 msec each) and number of microseconds into the minor cycle. This information allows computation of the actual time that the s/c clock was read.

Various delays affect the accuracy of the final clock correlation. After a major sync pulse, there is a one-bit delay before the leading edge of the packet is sent from the downlink card. For 16 kbps telemetry, this becomes a 62.5 μsec delay, for 1 kbps telemetry, this is a 1000 μsec (= 1 msec) delay. Prior to reaching, the transponder there is an NRZ-L to NRZ-M conversion whose delay must be measured. For spacecraft using a first or second generation TDRS S-band transponder, the transponder delay was under a microsecond and usually ignored. For TERRA, the convolutional encoding is done in the transponder, hence there will be about a three-bit delay that must be accounted for ($SC_{RTN\ transponder\ delay}$ in Section 4.4).

GT delays involving both the WSC and EDOS are different for TERRA than for other projects. The plan for TERRA is to not use NASCOM blocks (which contain a ground receipt time in their header). The spacecraft housekeeping and engineering 16 kbps I and Q channel data is to be sent via modem to the EDOS at GSFC on a T1 line along with a WSC generated IRIG B time code granulated to the microsecond. Since a T1 line operates at 1.544 Mbps ($T1_b = 0.67$ μsec), it is not unreasonable for the reconstructed I, Q and IRIG channels at the EDOS to contain no more than a microsecond of timing skew. Equipment at the EDOS can then accurately apply the GRT to the telemetry data since all three channels undergo the same delay while traveling to the EDOS. The SN OPM-52 contains the time delay from the ground terminal antenna at a WSC SGLT to the time tag at the MDM. Since TERRA is not using the MDM and its associated NASCOM blocks, a separate calculation is required to establish the delay from the ground terminal antenna to the point where the telemetry is extracted from the normal data path. This delay is different for SSA and MA and will be very close to the OPM-52 reported value (Reference 10).

TDRS Ground Terminal Return Data Delay 103.8 T_b + 6 μsec. for SSA and 102.8 T_b + 60 μsec. for MA.

Convolutional decoding is done at the WSC and its delay is 101.8 T_b of the above delay. The spacecraft delay for both convolutional and R-S coding is established during spacecraft integration & test. The R-S decoding delay at the EDOS must be established.

TERRA S/C Internal Delays

	TIME DELAY	DESCRIPTION	Delay (nS)	Variability (nS)	Recommended Value (nS)
A	FWD_HGA_ANT	Forward link delay between SBT (SBT2) and HGA antenna	0.037	+0.003 Note 1	0.037
A'	FWD_OMNI_ANT	Forward link delay between SBT (SBT1) and OMNI antenna	0.018	+0.006 Note 1	0.018
B	RTN_HGA_ANT	Return link delay between SBT (SBT2) and HGA antenna	0.037	+0.003 Note 1	0.037
B'	RTN_HGA_ANT	Return link delay between SBT (SBT1) and OMNI antenna	0.018	+0.006 Note 1	0.018
C	PN_SBT_RT	PN Epoch round trip delay internal to the SBT	1.2775	+0.00113 -0.0	1.278
D	PN_SBT_TO_CTIU	Delay from PN Epoch input to SBT to SBT PN Epoch Pulse output to the CTIU.	0.907	<TBD>	0.907
E	16K_GN_SBT	Worst case SBT data downlink delay or latency in the SBT at 16K in STDN mode. (Not applicable for EOS-AM mission)	140.97	+0.0 -0.0313	N/A
F	16K_TDRS_SBT	Worst case SBT data downlink delay or latency in the SBT at 16K in TDRS mode.	63.22	+0.0 -0.0313	63.21
G	1K_GN_SBT	Worst case SBT data downlink delay or latency in the SBT at 1K in STDN mode. (Not applicable for EOS-AM mission)	225.03	+0.0 -0.0313	N/A
H	1K_TDRS_SBT	Worst case SBT data downlink delay or latency in the SBT at 1K in TDRS mode.	1000.72	+0.0 -0.0313	1000.71
I	CTIU_PN_SAMPLE	Time delay internal to CTIU from receipt of PN Epoch until sample is valid. (Until s/c clock is read)	0.05	+1.5 -0.05	0.75
J	16K_BIT_DELAY	Single bit time delay at 16K	93.77	N/A	93.77
K	1K_BIT_DELAY	Single bit time delay at 1K	1500.02	N/A	1500.02
L	16K_PACKET_DELAY	Single packet time delay at 16K	1.024E6	N/A	1.024E6
M	1K_PACKET_DELAY	Single packet time delay at 1K	2.048E6	N/A	2.048E6
N	CTIU_TLM_DELAY	Delay within CTIU from packet generation until transferred out, through the hardware, to the SBT. @ 1K=M+K, @ 16K=L+J	M+K L+J	TBD	M+K L+J
P	PN_SBT_TO_CTIU	Delay of PN Epoch from output of SBT to input of CTIU. (Assuming zero for calculations, included in other parameters)	0	0	0
Q	PN_SBT_RETURN	PN Epoch return delay within the SBT. Q=C-D	0.3705	TBD	0.3705
R	PN_DEL_TWINDOW	Time between Major Cycle Start and when the CTIU begins listening to the SBT PN Epoch Pulse Interface.	0	TBD	0
S	PN_DEL_T2SC	Time between When the CTIU begins listening to the SBT PN Epoch Pulse Interface and when the clock is read (sctPN_DEL_T2SC = t2sc - twindow =8000*CDH_NR_ACT_PN_MC+ CDH_NR_ACT_PN_TIME).	variable	TBD	
T	Not Used	The Letter T is not used in this table.	Not Used		
U	Unknown_Variable_1	This is the unknown and unpredictable variable amount of time between the opening of the CTIU PN Epoch Pulse Sampling Window (twindow) and the time the CTIU receives a PN Epoch Pulse from the SBT. This variable is the result of the fact that the TGT transmission of PN Epochs is completely independent of S/C timing cycles.	variable		
Note		Includes differences between SBT1/SBT2 (0.001), Zenith/Nadir (0.005), LHCP/RHCP (0.002)			
	OMNI	Value added for Nadir Omni instead of Zenith Omni	0.005		0.0
	SBT	Value added for SBT2 instead of SBT1	0.001		0.0
	HGA	Value added for RHCP instead of LHCP	0.002		0.0

6. 4 Interim Control Module (ICM)

The ICM is a component of the International Space Station (ISS). The ICM as built by the Naval Research Laboratory (NRL) utilizes "GPS time" as its time standard. The title of GPS time is something of a misnomer in that time is not received from the GPS constellation but is instead, merely referenced to the GPS epoch of January 6, 1980, 00:00:00. The main oscillator runs at 20 MHz. with an accuracy of 1 part in 10^6. As a result of the high frequency of the oscillator, the basic clock tick period is 50 ηsec.

The ICM Spacecraft Controller (ISC) produces a time tag that represents the first bit of the first frame of the ISC master frame (the time tag variable is designated RL_MF_TT). Note that there are 64 minor frames to the master frame. The ISC also time tags each PN epoch from TDRS with the GPS time of receipt. Variable RL_MF_TDRSS_TT_A/B represents the elapsed time (msec) between the receipt of an Epoch pulse from transponder A/B and the RL_MF_TT (Start of master frame). The clock (GPS time) is also read at the start of a master frame (with zero delay).

Additional information will be inserted as available.

6.5 Earth Observing System EOS PM-1

6.5.1 Summary

EOS PM-1 will use the User Spacecraft Clock Correlation System (USCCS) to set its several onboard clocks. Since they are all similar, we will discuss only one and understand that the same information applies to both and that the correlation process will be repeated for each. The question to be evaluated is whether the design for PM-1 contains the necessary components so that the clock correlation can be performed. It appears that the epoch ARM time is properly characterized for the USCCS and that it is properly characterized to initialize the USCCS. By "initialize" we mean that it can be used to do an RDD calculation which is needed when the clocks are first turned on or if they are reset.

6.5.2 PM –1 USCCS Clock ARM Time

In order to allow the ground software to evaluate which of the many PN epochs were used to trigger the spacecraft clock reading, the spacecraft system disallows the epochs from having an effect until a particular time or event, the clock ARM time. According to the TRW document EOS PM-1 Spacecraft Time Correlation dated February 17, 1999, the ARM time is from 249.806 ms to 249.624 ms before the beginning of a CADU of VCID 2 with the sequence count ending in 1111. At a data rate of 1024 bps with no CADUs except VCID 2, a count of xx…xx1111 will occur once every 32 seconds. If other data is also flowing, there will be CADUs with VCIDs other than 2 and the interval will be greater than 32 seconds. This is not a problem but will cause some inconvenience during testing if the interval is not uniform.

This instability of 249.806 – 249.624 = .182 ms = 182 us will have a small but not serious effect on the selecting of the correct epoch. Since the epochs are 85 ms apart, there is a 0.182/85 = 1/467 chance that the wrong epoch will be selected during the correlation process. A single TTM

contains 255 seconds of data so with 32 seconds between the epoch being ARMed there will be 8 useful correlation events. Once in a while one of these will show a clock error of 85 ms different from the others. This should not be averaged but simply ignored. In general, the ground software will not average the various correlation results but will eliminate the outlying ones.

6.5.2.1 Timing Reference Point

Instead of specifically implementing the RDD method, PM-1 has indirectly made it available via the ARM time used for the USCCS.

6.5.2.2 Time Packet

A time packet with a specific APID = TBD will be contained in the VCID = 2 telemetry. The packet will contain the spacecraft clock reading at the ARM time and the spacecraft clock reading at the first epoch after the ARM time. In order to avoid confusion during ground processing of the data, the packet will also contain the CADU sequence count, xx…xx1111, associated with the ARM time. Upon receipt on the ground, a ground receipt time (GRT) will be obtained and attached to the time packet.

6.5.3 Ground Processing

The time packet with the attached GRT will contain the bulk of the information that is needed to perform an RDD time correlation that is completely independent of the USCCS (independent of TDRSS epochs). For an accurate RDD calculation, the range time to the satellite at about ¼ second prior to the GRT is required. This range time, accurate to 0.2 us, is easily obtained from the TTM and may be obtained even if a USCCS calculation is not being performed. The project flight operations team simply requests the TTM by checking a particular box when they schedule a coherent TDRSS service. In the normal case where a USCCS calculation is being performed, the simplest way to get an accurate range time for the initial clock setting is from the TTM. This is because the TTM is already needed for the epoch times for the USCCS. Obtaining the range from orbit equations is circular logic, more complicated and less accurate since the orbit equations come from the measured range time contained in the TTM. Finally, the time packet with the attached GRT and the associated TTM are all that is needed to do: the initial USCCS calculation which requires an RDD calculation an independent RDD calculation and a day to day USCCS calculation which may also include an RDD calculation after the initial one.

6.5.4 Required Spacecraft Delays

Once the forward and return epochs are correlated with a given spacecraft clock reading, the errors and inaccuracies of the initial RDD calculation are no longer a factor. The final clock offset is limited by only a few USCCS related spacecraft delays. The TDRSS delays, in particular the TDRS forward and return propagation delay and the TDRSS ground terminal delay are well characterized and reported to nanosecond accuracy. The transponder forward and return delays are characterized by the manufacturer to nanosecond accuracy. Ground system software round off errors are kept to no more than a few microseconds. RDD related and ARM time errors are not a factor once proper epochs that triggered the clock reading are identified. In the end, the

clock error determination is limited by the accuracy of the knowledge of only a few USCCS related spacecraft delays.

It is the responsibility of the spacecraft contractor to compile data from subcontractors; analyze hardware, software and firmware; make spacecraft measurements and report these delays to NASA. Due to the subtleties of evaluating delays of the order of microseconds in circuits with software, firmware and interrupts, NASA requests that the plan for how these delays will be determined be shared with NASA.

6.5.4.1 Epoch delays

Transponder forward PN delay (receive)
Transponder return PN delay (transmit)
Transponder internal delay from time of epoch generation until pulse output
Delay from transponder output of time transfer epoch until clock is latched

> Above two delays are referred to as $T_{\text{User USCCS}}$ in the USCCS Users' Guide

6.5.4.2 ARM circuit delays

Delay from the generation of the leading edge of the first bit of CADU xx…xx1111 until that bit edge is radiated from the antenna. The portion of this delay thru the transponder is not the same as the "Transponder return PN delay (transmit)" listed above. The delay here is a data delay. This may be different for each transponder, will include the transponder propagation delay which may be obtained from the manufacturer and may be data rate dependent. This delay is referred to as $T_{\text{User RDD}}$ in the USCCS Users' Guide.

6.5.5 Testing

Since PM-1 uses TDRSS for command and tracking, it is expected that end to end TDRSS testing will be performed. USCCS requires a coherent TDRSS contact for clock correlation but may not require a coherent contact for parts of the clock testing, in particular control commands. Where parts of the USCCS clock circuits can be tested without the burden of a TDRSS contact, they should be so that the TDRSS testing can be kept on schedule.

6.5.5.1 Hard Line Clock Output

It is required that there be a method of reading the clock via hard line during testing. It will be necessary to compare the clock reading with UTC so that the absolute clock error is known. Usually a GPS clock is used as the reference. Do not confuse GPS time with UTC, the two are different by about 15 seconds because GPS does not contain leap seconds but some GPS clocks are corrected and output UTC.

6.5.5.2 Testing Commands

Demonstrating clock control including setting via "jam" command (set a specific time), via "delta" command (increase or decrease a current clock setting by a specific amount) and via frequency

change command will be required but need not be done during an end to end TDRSS test. The PM-1 project may agree to accept the hard line testing of the command by observing the changes in the clock hard line readings.

6.5.5.3 USCCS Clock ARM Circuit

Part of the ARM circuit may also be tested without the need for a TDRSS contact. When VCID = 2 CADU with sequence count xx…xx1111 is generated the epoch circuit is armed and a clock reading is taken (details above). This clock reading is placed in APID = TBD and output in the telemetry stream. Time tagging the telemetry output at the spacecraft in UTC will allow us to calculate the time the ARM function was executed by subtracting the known (measured) output delays. By comparing this calculated ARM time (UTC) with the time in the telemetry packet we calculate the clock error. This error should agree with the known clock error from the hard line clock output discussed above. This is the same as an RDD clock correlation with a 0 space propagation delay.

6.5.5.4 Ground Software

Much of the software in the ground system that is currently being written for EOS TERRA (AM-1) will be reused for PM-1; however, differences in the telemetry CADUs and the time packet structure will require some unique software for PM-1. This must be tested prior to end to end TDRSS testing of the spacecraft to insure that the clock correlation function can prove or disprove the spacecraft and the reported spacecraft delays.

Section 7. Operational Considerations

7.1 MOCC Operations

Details of each MOCC will differ. Specifics of various spacecraft and the associated MOCC are given in Section 6.

7.2 TDRSS Configuration

For the OPM-66, time transfer must be specified in the (Scheduling Order) SHO. Since the forward and return range epochs are synchronized at the User spacecraft only during a coherent tracking service, the SHO must specify tracking. The User spacecraft transponder must be in the coherent mode. A forward only or return only service can not be used for USCCS.

When using the RDD method, it is recommended that clock correlation be done during tracking passes that are otherwise required by FDF for orbit determination. These passes require coherency for tracking, hence, the OPM-66 will be available. If RDD is performed on a return only pass, the range as a function of time can be obtained from the FDF.

Abbreviations and Acronyms

ADPE	Automatic Data Processing Equipment
AOS	Acquisition of signal
APID	Application Identification number
CADH	Command And Data Handling (subsystem of a spacecraft)
CADU	Channel Access Data Unit
CCSDS	Consultative Committee for Space Data Systems
CGRO	Compton Gamma Ray Observatory
Chip	l bit of PN range data pattern
D2B	Used by CGRO to represent the time between the first bit of a major frame and the arrival of an epoch that triggers a spacecraft reading
DCE	Doppler Compensation Enabled
DCI	Doppler Compensation Inhibited
DIS	Data Interface System
DPSS II	Data Processing Services Subsystem II
EDOS	EOS Data and Operations System
EOS	Earth Observing System
EOS-AM	EOS Morning Crossing Satellite (renamed TERRA)
Epoch	(See PN epoch)
ERT	Earth receipt time (Same as GRT)
FDF	Flight Dynamics Facility
GCE	Ground Communications Equipment
GPS	Global Positioning System
GRO	Gamma Ray Observatory (see CGRO)
GRGT	Guam Remote Ground Terminal
GRT	Ground Receipt Time (Same as ERT)
GSFC	Goddard Space Flight Center
GT	Ground Terminal (generic name for both STGT and WSGTU)

HST	Hubble Space Telescope
Hz	Hertz (cycle per second)
ICM	Interim Control Module (of ISS)
IP	Internet Protocol
IR	Integrated Receiver
ISS	International Space Station
JSC	Johnson Space Center
LEO	Low earth orbit (satellite)
LOS	Loss of signal
MA	Multiple Access Service
MABE	MA beam forming equipment
MDM	Multiplexer/DeMultiplexer
MDP	Modulator Doppler Predictor
MO	Master Oscillator
MOCC	Mission Operations Control Center
MSOCC	Multi Satellite Operations Control Center
NAM	Network Advisory Message
NASCOM	NASA Communications (replaced by NISN)
NCC	Network Control Center at the GSFC
NGT	NASA Ground Terminal (Early version of DIS)
NISN	NASA Integrated Services Network
NRL	Naval Research Laboratory
ηsec/ηs	Nano Second, 1 billionth of a second, 1E-9 sec.
OPM	Operational Procedure Message
PB1	NASA standard time format, (27 bits of ms of the day, no μs portion). Used for seconds portion of forward and return epoch information in OPM-66.
PB4	NASA standard time format, (27 bits of ms of day, 10 bits of μs of ms). Used for Ground Receipt Time Tag at the MDM
PMP	Pre Multiplexing Processor (CGRO: format conversion, convolutional encoding)

PN	Pseudorandom noise
PN epoch	Portion of the PN pattern containing 18 ones in a row. Pulse emitted by transmitter or receiver in time synchrony with the 18 ones in a row.
POCC	Project Operations Control Center (see also MOCC)
R-S	Reed Solomon (coding technique)
RCTD	Return Channel Time Delay
RDD	Return Data Delay
RF	Radio Frequency
RF SOC	RF Simulation Operations Center
RIU	Remote Interface Unit
RXTE	Rossi X-Ray Timing Explorer
RZS	Range Zero Set, referred to as FWD/RTN PN time delay in OPM-66
SA	Single Access
SAW	Surface Acoustic Wave
SC	Spacecraft
SHO	Scheduling Order
SN	Space Network
SOC	Simulations Operations Center
SSA	S-band Single Access Service
STGT	Second TDRSS Ground Terminal
SUPIDEN	Support Identification code
T	Forward epoch period, generally not constant
t_1	Time of a particular forward epoch that triggered reading on S/C
t1	Time of a reported forward epoch
t2	Time epoch arrives at user spacecraft based on GT clock
t_2	Time spacecraft clock is read based on GT clock with appropriate corrections included.
T_3	Return epoch period, generally not constant
t_3	Return time of a particular epoch that triggered reading on S/C
t3	Time of an arbitrary return epoch at GT based on GT clock
TAC	Telemetry and Command Computer (in MSOCC)

TCP	Transmission Control Protocol
TDRS	Tracking Data and Relay Satellite
TDRSS	Tracking Data and Relay Satellite System
TERRA	EOS Morning Crossing Satellite (was EOS-AM1)
TLM	Telemetry Data transmitted from the satellite to ground
TPN	Period of a PN code Pattern
TPOCC	Transportable POCC
TRMM	Tropical Rainfall Measuring Mission
TTM	Time Transfer Message from GT, contains delta t1 and delta t3
TTU	TDRS Timing Unit (CGRO's term for their spacecraft USCCS equipment)
UCTF	UTC correction factor
UDP	Unacknowledged Data Protocol
μs/μsec	Microsecond, 1 millionth of a second, 1E-6 *second
USCCS	User Spacecraft Clock Calibration System
USO	Ultra Stable Oscillator
USS	User Services Subsystem
UTC	Universal Time Coordinated
VC	Virtual channel
VCDU	Virtual Channel Data Unit (CCSDS telemetry Frame)
WSC	White Sands Complex. STGT and WSGTU (and DIF)
WSGTU	Upgraded White Sands Ground Terminal

Appendix A.
OPM-66

Appendix A. OPM-66

Time Transfer OPM-66 Specification

Excerpted from STGT phase II Specification DCN-04 31 August 1990 Ref 11.

9.3.4.5 Time Transfer, OPM - Class 66. This message shall be used to provide time transfer data to NASA. This message shall be transmitted to NASA within 1 minute of termination of service for which time transfer was requested in the SHO. Multiple blocks may be required.

Table A-1. OPM-66

No. of Bytes	Data Item	Comment
12	OPM Header	
11	OPM Subheader	
4	Forward PN time delay (Binary, LSB = 10 nanoseconds)	
4	Return PN time delay (Binary, LSB = 10 nanoseconds)	(RZS)
1	Number of Samples (Binary, 20-255)	
5	NASA PB-1 Time Sample (Binary)	

1	Receiver PN Lock
	  0 = No Lock
	  1 = Lock	

3	Forward Delay Time (Binary, LSB = 200 nanoseconds)	t_1'
3	Return Delay Time (Binary, LSB = 200 nanoseconds)	t_3'
32 + 12n	Repeat last 12 bytes for each measurement	

The next page, table A-2 shows Time Transfer Message Format, has been excerpted from Ref 4: STDN No. 230.1 (Rev 3 page B-38) detailing the actual byte count and location as specified and constructed. This information is critical in design and coding of POCC software.

Table A-2. Time Transfer Message Format OPM-66 - NCC to POCC

Item Number	Number of Bytes	Data Items	Range of Values
1	2	Message type	92 = Performance Message Data
2	7	Message ID	A unique number used to reference this message
3	2	Message Class	**66** = Time Transfer Message
4	7	SUPIDEN	Refer to STDN No. 808
5	3	TDRS ID	TDE = TDRS East TDW = TDRS West TDS = TDRS Spare 171 = TDRS 171 275 = TDRS 275
6	1	Service Support Subtype	0 = MA 1 = SSA1 2 = SSA2 3 = KSA1 4 = KSA2
7	2	MA Return Link ID	00 = not MA return 01 thru 10 MA return link ID
8	4	Forward PN Time Delay (RZS)	LSB = 10 nanoseconds (expressed in binary format)
9	4	Return PN Time Delay (RZS)	LSB = 10 nanoseconds (expressed in binary format)
10	1	Number of occurrences	020 thru 255 (expressed in binary format)
11	5	NASA PB-1 Time Sample	(expressed in binary format)
12	1	Receive PN Lock	0 = No Lock 1 = Lock
13	3	Forward Delta Time Time to 1st Epoch from hack	LSB = 200 nanoseconds (expressed in binary format)
14	3	Return Delta Time Time to 1st epoch after 1st forward epoch	LSB = 200 nanoseconds (expressed in binary format)
15	Variable	Time Transfer Data	Repeat items 11 through 14, n-1 times as indicated by the value in Item10.

Appendix B.

OPM 52, OPM 62

WSC Þ NCC, NCC Þ POCC

Appendix B.

OPM 52, OPM 62 WSC Þ NCC, NCC Þ POCC

Return Channel Time Delay Measurement Message Format OPM-62

Item Number	Number of Bytes	Data Items	Range of Values
1	2	Message type	92 = Performance Data Message
2	7	Message ID	A unique 7-character number used to reference this message
3	2	Message Class	**62** = Return Channel Time Delay Measurement Message
4	7	SUPIDEN	Refer to STDN No. 808
5	3	Station	TDE = TDRS East TDW = TDRS West TDS = TDRS Spare 171 = TDRS 171 275 = TDRS 275
6	1	Service Support Subtype	0 = MA 1 = SSA1 2 = SSA2 3 = KSA1 4 = KSA2
7	2	MA Return Link ID	00 = not MA return 01 through 10 = MA return link ID
8	7	Time Delay at Service Start, I Channel (or K-Shuttle, Channel 3 or S-Shuttle	LSB = 1 microsecond
9	7	Time Delay at Service Start, Q Channel (or K-Shuttle, Channel 1)	LSB = 1 microsecond
10	7	Time delay at Service Start, K-Shuttle, (Channel 2)	LSB = 1 microsecond
11	7	Time Delay at Service Stop, I Channel (or K-Shuttle, Channel 3 or S-Shuttle)	LSB = 1 microsecond

Taken from Ref. 4

Appendix C.

USCCS Orbital Correction Algorithm

Appendix C. USCCS Orbital Correction Algorithm

USCCS Orbital Correction Algorithm

Outline

The User Spacecraft Clock Calibration System (USCCS) is a closed loop method for calibrating one clock against another, typically a spacecraft clock and an earthbound one. This system is used by the Compton Gamma Ray Observatory (CGRO). The basic concept of the method is extremely simple. A pulse is transmitted from the ground at time t_1, which is measured. It arrives at a spacecraft at some time t_2, which is unknown. The spacecraft transponder immediately retransmits the pulse to the ground where its arrival time, t_3, is measured. Upon receipt of the pulse at the spacecraft, the spacecraft's clock is read and the reading, t_{2sc}, is transmitted to the ground. On the ground, t_2 is calculated from t_1 and t_3 and compared to t_{2sc} for calibration. The pulse arrival time at the spacecraft, t_2, is approximately half way between t_1 and t_3. For a low earth orbiting (LEO) spacecraft and a geosynchronous relay satellite, the correction to half way between t_1 and t_3 does <u>not</u> depend on the LEO spacecraft velocity or its Doppler shift. The correction does depend on the LEO position and the fixed quantities: earth rotational speed, geosynchronous relay satellite's rotational speed, relative position of earth station, and, of course, the speed of light. The purpose of this appendix is to evaluate t_2.

The required correction of up to about 1 μsec., is asymmetric with the relative position of the LEO and relay satellite and, thus, only indirectly related to the Doppler, which is almost symmetric. The Doppler can be used to determine the relative orbital position, which can then be used to determine the required correction.

Doppler

In order to evaluate the corrections required to t_1 and t_3 in to calculate the time it was at the User spacecraft, consider the following. An object (User spacecraft) is moving away from a fixed observer at a constant velocity, Figure C-1.

The frequency transmitted from the observer, f_1, and received by the observer, f_3, are different (Doppler), but the epoch (or zero crossing) is at the User at a point in time, t_2, which is exactly halfway between the time it leaves the observer, t_1, and the time it returns to the observer, t_3.

Note that the relative velocity, v, between observer and User spacecraft can be determined from the observer's measurement of forward and return PN periods, T_1 and T_3, respectively Figure C-1. For CGRO USCCS, v is not constant (the observer on the Earth is also not in an inertial reference frame).

TDRS-E
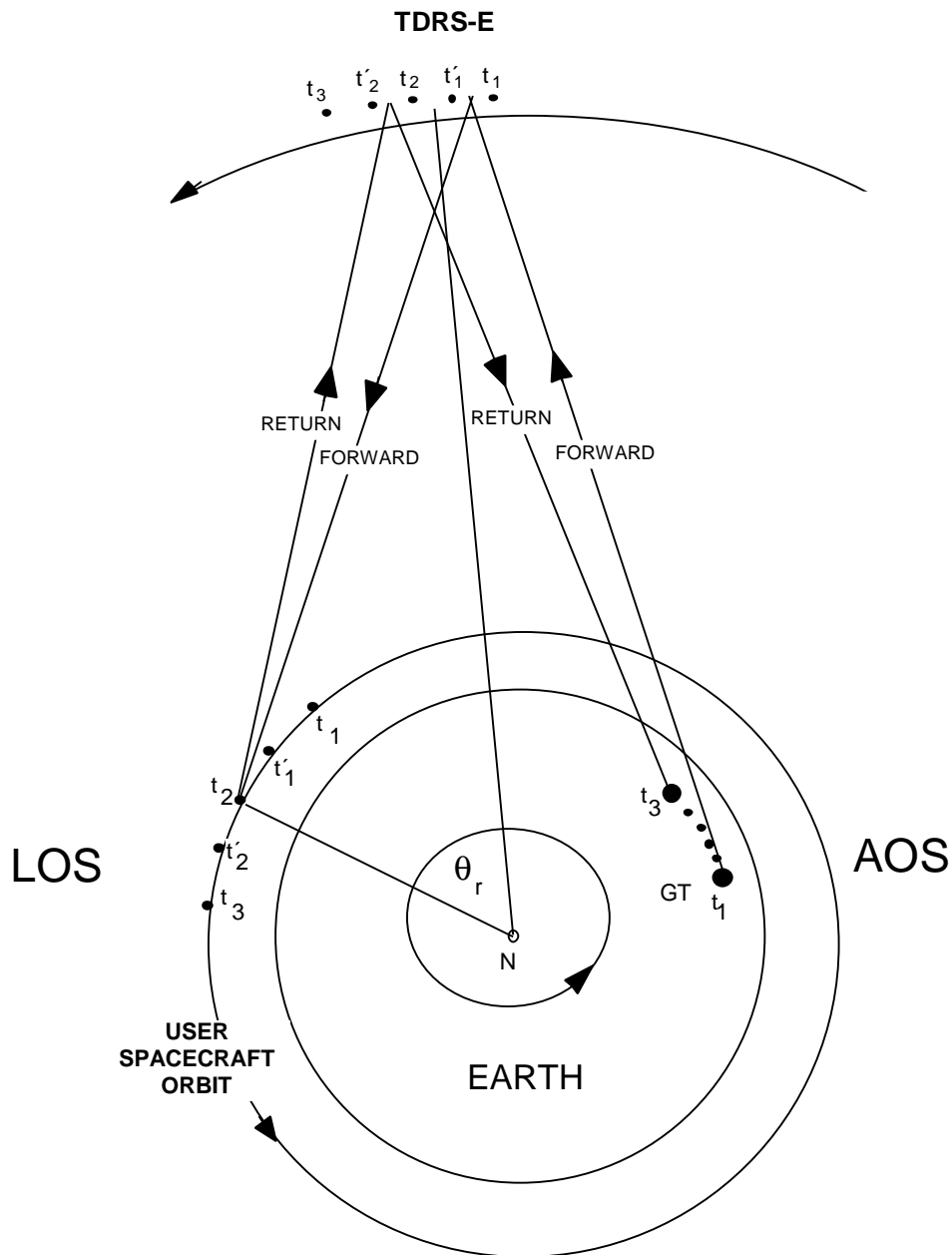
Figure C-1. RF Signal Path

For an observer at the WSC on a slowly rotating Earth and a spacecraft in orbit, the above concepts are at least approximately true. For USCCS, the important concept is that an epoch that leaves the ground at time t_1 and arrives back on the ground at t_3 was at the spacecraft approximately half way in between.
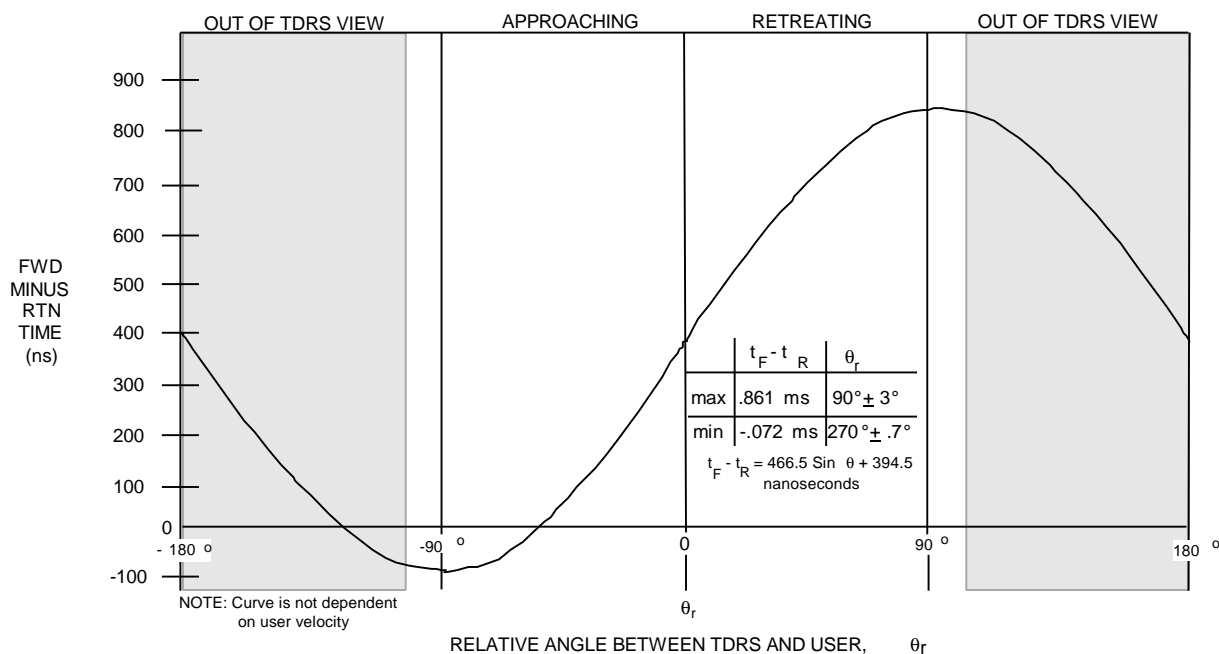
$$t_2 \; = \; t_1 \; + \; \frac{t_3-t_1}{2} \; = \; \frac{t_1+t_3}{2} \tag{C-1}$$

For the constant velocity case, this equation is exactly true no matter how fast the user spacecraft is moving. Simulations using Earth, TDRS, and User spacecraft actual motion show the error in Equation C-1 to be less than 1 μsec. and, again, independent of the user spacecraft motion, Figure C-1. Since the Earth is slowly rotating and the round trip signal travel time is only 0.5 seconds, the earth observer can be considered to be inertial, approximately within 1μsec.

The desire for greater accuracy requires an inertial reference frame. The remaining discussion does not cover relativistic considerations, which are of the order v^2/c^2 and similarly ignores second order Doppler effects. The concepts involved in the true motion of the Earth, TDRS and user are now discussed.

The three bodies are shown from above the North Pole of the Earth with the earth center being the center of the reference frame in Figure C-1. Because of the Earth's curved path (orbit) around the sun, this also is not a true inertial reference frame, but the remaining errors are several orders of magnitude below the desired accuracy.

Figure C-1 shows that the forward path and return path are not the same. The GT to TDRS and TDRS to GT portions appear the same, but the TDRS to user and user to TDRS portions are clearly not the same. Since the forward and return paths are different, the signal that left the ground at t_1 and returned at t_3 is not at the spacecraft exactly half way in between. Since the signal is at the user for only an instant of time at t_2, it may be intuitive that the difference in forward and return time is independent of the user spacecraft velocity. This is similar to the constant velocity example given earlier and has been confirmed for rotating bodies via simulation.

	t_F-t_R	θ_r
max	.861 ms	90°± 3°
min	-.072 ms	270°± .7°

$t_F - t_R = 466.5 \sin \theta + 394.5$ nanoseconds

NOTE: Curve is not dependent on user velocity

RELATIVE ANGLE BETWEEN TDRS AND USER, θ_r

Figure C-2. Difference Between Forward and Return Signal Travel Time (t_F-t_R)

The difference in forward and return travel time is due to both Earth and TDRS motion. Clearly, the TDRS motion during the 1/4 second that the signal travels from the TDRS to user and back to TDRS causes a difference in forward and return travel time. In addition, a more subtle effect is the difference between the GT to TDRS and TDRS to GT travel time. As a signal traveling from

the GT to TDRS-E, for example, moves through space, the TDRS is moving away. Thus, the distance traveled by the signal is greater than the instantaneous GT to TDRS distance. Similarly, as a signal travels from TDRS-E to the GT, the GT moves toward the signal so the distance traveled by the signal is less than the instantaneous distance. Since the TDRS and GT are always in fixed relative positions, the forward travel time of one pulse is the same as the forward travel time of the following pulse. Similarly, the return travel time from TDRS to GT for successive pulses is the same. For TDRS-E, the forward time is 0.395 µsec. longer than the return time. For TDRS-W, the values are reversed. The portion of the signal path between the TDRS and the user is now considered. Computer simulation shows the signal travel time from TDRS to the user to be a maximum of 0.466 µsec. longer than the travel time from the user to the TDRS. This occurs at approximately the Loss of Signal (LOS) point. At Acquisition of Signal (AOS) the values are reversed because the user is approaching the TDRS and the TDRS to user time is less than the user to TDRS portion.

The net effect of combining the GT to TDRS and TDRS to user travel times is such that for TDRS-E at LOS the forward travel time is 0.86 µsec. longer than the return travel time. At AOS it is about 0.072 µsec. less, Figure C-1. For TDRS-W, the conditions are reversed.

As in the constant velocity example of Figure C-3, the forward and return PN periods, T_1 and T_3 can be used to determine the radial component of the User's velocity. In the real case, the complete motion as shown in Figure C-1 must be taken into account, but the results will be approximately equal to that given by the equation for v in Figure 10.

The maximum Doppler effect will cause the PN period at the spacecraft to vary by about 2 µsec. from the period transmitted from the GT. Thus, the return PN period at the GT will be a maximum of 4 µsec. different from the transmitted period. Although the PN periods as measured at the GT reflect the velocity of the user spacecraft, Figure C-2, their magnitude does not directly relate to the correction needed in the USCCS to determine t_2. The values of T_1 and T_3 serve only to indicate where the user is in his orbit relative to TDRS. The geometry of Figure C-1, the TDRS and Earth rotation, must then be used to calculate the sub-microsecond correction needed to obtain the correct value of t_2. That is, T_1 and T_3 at a given time are used to find v. The relative orbital angle between TDRS and the User, Figure C-3, can be determined knowing the value of v. Once the angle is known, the difference between the forward and return travel time, $t_F - t_R$, can be found from Figure C-1, and used to find the correction required for Equation C-2.

$$t_2 \;=\; \frac{t_1 + t_3}{2} \;+\; \frac{t_F - t_R}{2} \tag{C-2}$$
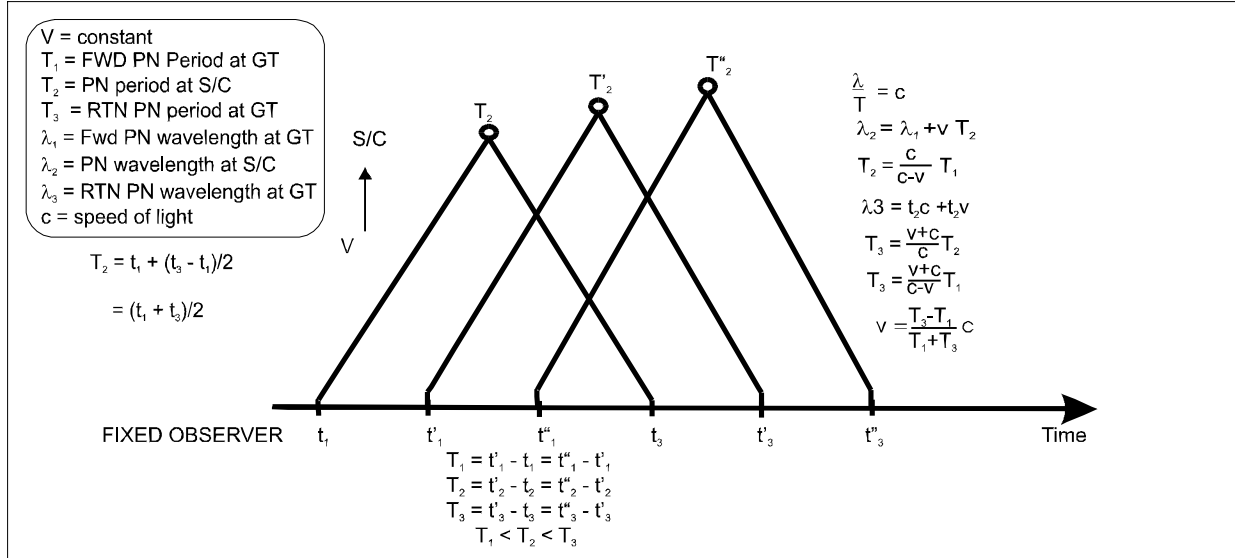
Figure C-3. Signal Path for Object at Constant Velocity

Correction Term

Using Figures C-1, C-2 and C-3, the correction term $t_F - t_R$ can be modeled as follows. The User velocity as seen from TDRS varies sinusoidally as

$$v \cong v_u \times \sin \frac{\pi}{2} \frac{\theta_r}{\theta_c} \quad \text{where} \quad -100^o <= \theta_r <= 100^o \tag{C-3}$$

where:

θ_r is the relative angle between the TDRS and user measured from earth center.

$\theta_c = \cos^{-1}\left(\dfrac{r_u}{r_T}\right)$ is the relative angle at which the user is moving toward or away from TDRS.

v_u is the user's orbital speed.

In terms of T_1 and T_3
$$v \cong \frac{T_3 - T_1}{T_1 + T_3} c \tag{C-4}$$

Equation C-3 is used to solve for
$$\theta_r \cong \frac{2\theta_c}{\pi} \times \sin^{-1}\left(\frac{v}{v_u}\right) \tag{C-5}$$

where v is known in terms of T_1 and T_3 from Equation C-4

From Figure C-2, the correction term $\quad t_F - t_R \cong 0.4665 \times \sin(\theta_r) + 0.3945\,\mu s \tag{C-6}$

Using Equation C-2 with this correction yields about two orders of magnitude correction over Equation C-1. T_1 and T_3 are sufficiently slowly varying that $T_1(t_1)$ and $T_3(t_3)$ will suffice.
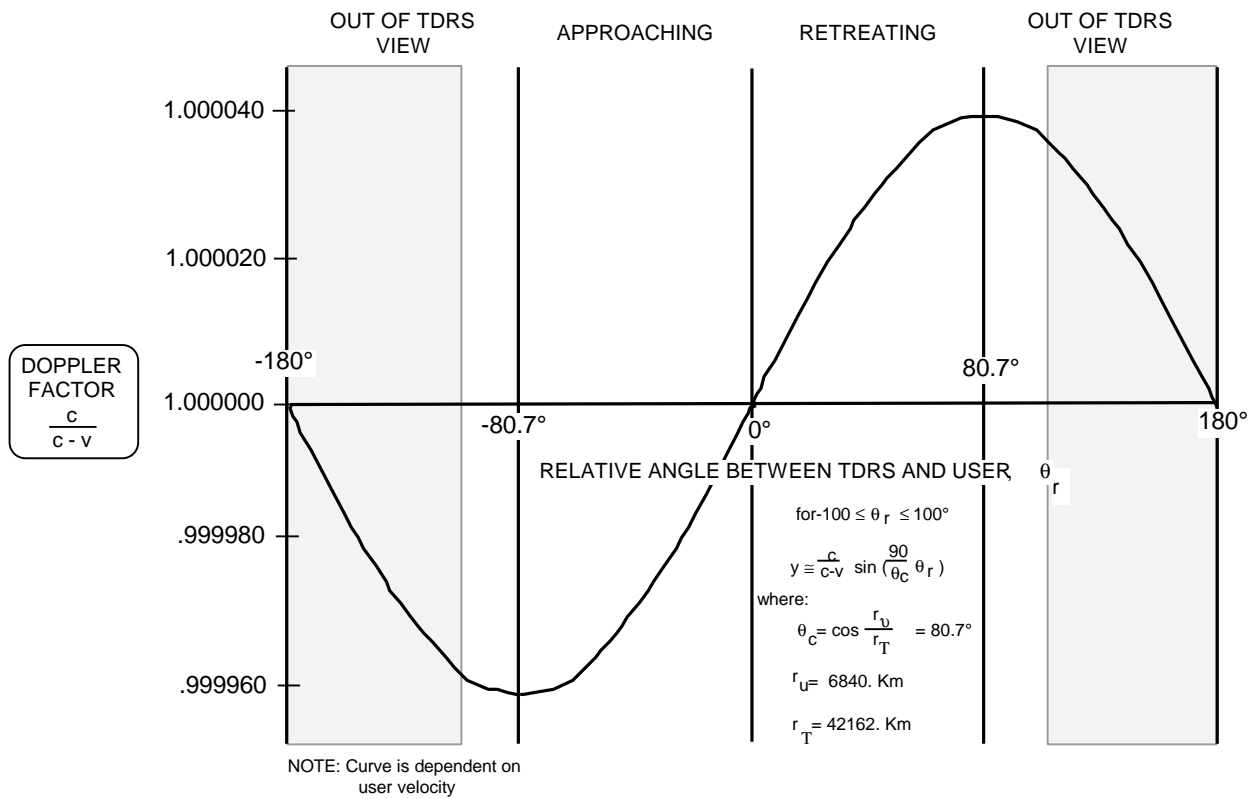
Figure C-4. Doppler Factor $\dfrac{c}{c-v}$

Filename: TUDIST.BAS   Date 7/19/91

    Written by Victor J Sank FH&A   Last update 7/26/91

    Track an epoch traveling from WSGT to TDRS to a USER and back to WSGT by an inertial observer.

    At T1 epoch leaves WSGT

    T1P FWD epoch at TDRS

    T2 epoch is at USER

    T2P RTN epoch at TDRS

    T3 epoch is back at WSGT

Configuration: The user satellite, TDRS and the earth station rotate in the same plane, the equatorial plane, at their respective speeds. The coordinate system is centered at the earth center. At time equals zero, both TDRS and the User are at an angle of zero and the ground station is at an angle of 65 degrees to simulate the approximate the relationship between TDRS-E and the WSGT. An epoch is transmitted on each one second mark and its time of arrival at each of the moving satellites is calculated by iteration.

The effects for a non-equatorial user orbit will be less than that calculated here. For example, a polar user orbit for which the orbital plane is approximately normal to TDRS will only contain WSGT to TDRS effects since the TDRS to user distance remains approximately constant.

Improve accuracy of OMEGAT# and RW#   8/22/91
Add velocity calculation based on altitude.   9/18/91
Update documentation   9/30/91

```
C# = 299792.48               'KM/SEC
PI = 3.141592653589793
OMEGAT# = .000072921159      'RAD/SEC
OMEGAU# = .00111             'RAD/SE (typical LEO)
OMEGAW# = OMEGAT#            'RAD/SEC
RE# = 6378.                  'KM
RW# = 6385.642               'KM
H# = 450.                    'KM
PRINT
PRINT
INPUT "Enter User altitude in Km "H#
RU# = RE#+H#
RT# = 42162.                 'KM

MU# = 398601.2               'KM³/SEC² = G Me
W# = SQR(MU#tRU#)            'Orbital velocity KMtSEC
OMEGAU# = Vu# RU#
PRINT
```

```
PRINT "User orbital velocity is ";USINGn##/J/J1#JIII Km/sec";W#;
PRINT n = ";USINGn##.JJJJIIIJJflJI Radtsec";OMEGAU#

DWT# = 40000.
DTW# = DWT#
TOPN# = 261888*221*96t(31*2106406250#)'Nominal PN PERIOD
OT2# = 0
OT3# = 0
PRINT "TPN = ";TOPN#

100 ODTU# = 35322.
    DELT = 20                  'SEC
    TMIN = 000
    TMAX = 7000                'SEC
    PRINT

110 INPUT " ENTER START TIME (SEC): ";TMIN
INPUT  "ENTER END TIME (SEC): ";TMAX
INPUT "ENTER INTERVAL (SEC): ";DELT
IF DELT = 0 GOTO 110
DELT# = DELT
PRINT "TYPE CTRL-BREAK TO QUIT"

FOR IT = TMIN TO TMAX STEP DELTA 'T IN SEC
T# = IT
T1# = T#
PRINT "t1 = n;T1#;nsec TDRS and User in line at t1 = 0.0"
PRINT USING " #./IIII/I/II/IIII~IIU;T1#-IT";
T1PN# = (INT(T1#tTOPN#)+1+*TOPN#

TIME SIG LEAVES WS

THETAW# = OMEGAW#*T# -65.*PI*180. 'WSGT POSITION AT T
XW# + RW#*COS(THETAW#)
YW# + RW#*SIN(THETAW#)
RCW# + SQR(XW#^2 + YW# ^ 2)
T# = T# + DWT#/C#                 'EST TIME FWD SIG AT TDRS
FOR IWT = 1 TO 100
THETAT# = OMEGAT#*T#
XT# = RT#*COS(THETAT#)           'TDRS POSITION AT EST TIP
YT# = RT#*SIN(THETAT#)

DWT# = SQR((XT#-XW#)2 +(YT#-YW#)2)
TWT# = DWT#/C# +T1#
T# = T# - (T#-TWT#)t2
PRINT "DWT = ";USINGHIII~Lt~tff";DWT#
IF ABS(T#-TST#) < .000000001 THEN GOTO 400
NEXT IWT
```

```
400 T1P# = T#
'  TIME FWD SUG AT TDRS

PRINT "XW,YW,RCW,THETAW";XW#;YW#;RCW#;THETAW#
PRINT "XT, YT";XT#;YT#
PRINT "T1P=T1="USING"#.ttfftt7~#;T1P#-T1#
PRINT "WT="USING "#.~IIJ~`IIIIII";T#-IT

DTU#=ODTU#
T#=T#+DTU#/C#
FOR IU= 1 TO 100
THETAU# = OMEGAU#*T#
XU#=RU#*COS(I~IETAU#)
YU#=RU#*S~(I~IETAU#)
DTU#=SQR((XT#-XU#)^2+(YT#-YU#)~2)
TU#=DTU#/C#+T1P#
PRINT IU,T#,TU#
INPUT ANS$
T#=T#-(T#-TU#)/2
IF ABS(T#-TU#)<.0000(O001 THEN GOTO 500
NEXT IU

500 T2#=T#

'EXT TIME FWD SIG AT USER

PRINT "XU,YU",XU#;YU#
PRINT H t2=NUSING~#/IJJIJJI1~JIJIJJJJH;T#-IT
TPN2#=(T2#-OT2#)/DELT#
OT2#=T2#
PRINT n TPN2 n;USINGu# ###IJJJJJ~JJJJJH;TpN2#

DUT#=DTU#            'INITIAL EXTIMATE OF T2P
T#=T#+DUT#/C#      TIME RTN SIG AT TDRS
FOR IUT=1 TO 100
THETAT#=OMEGAT#*T#
XT#=RT#*COS(THETAT#0
YT#=RT#*SIN(THETAT#)

DUT#=SQR((XT#-XU#)^2 +(YT#-YU#)^2
PRINT"DTU# H;DTU#;"DUT#;DUT#;H D/C";DUT#/C#
UT#=DUT#/C# + T2#
PRINT IUT;"T EST N;T#;H D/C TO TDRS AT T "UT#
T#=T#-(T#-UT#)/2
IF ABS(T#-UT#)<.000000000 THEN GOTO 600
NEXT IUT
600 T2P# = T#
```

```
PRINT n XT,YT H;XT#;YT#
THETAU = THETAU#*180/PI                 'AN~E TO USER AT T2
THETAT = THETAT#* 180/PI                'ANGLE TO TDRS AT T2'
PRINT u REL ANGLE = U;USING H~.##N;THETAU-THETAT;
PR~T USING n THETAU = U;USING H~;THETAU-THETAT;
PRINT "t2P-"USING N#.IIIIIIIIJIJJJJ##U;T#-IT

T# = T# + DWT#/C#                       'INITIAL EXT FOR T3
FOR ITW= 1 TO 1200
THETAW#=OMETAW#*T#-65.*PI/A80.          'WSGT POSITION AT T
YW#=RW#*SIN(THETAW#)
XW# = RW#*COS(I~TAW#)
RCW#-SQR(XW#A2 + YW# 2)
DTW# = SQR((XT#-XW#)2 +(YT#-YW#) 2)
TTW#= DTW#/C#+T2P#
T#=T#-(T#-TTW#)/2
PRINT NDTW = ";USINGU#####.####";DTW#
IF ABS(T#-TTW#_<.000000001 THEN GOTO 700
NEXT ITW
700 T#2 = T#
PRINT "XW,YW,RCW,THETAW";XW#;YW#;RCW#;THETAW#
PRINT n t3="USING "#.#IIIIIIIIIIIIIIIIu;T3#-IT
PRINT "t3-t2P=";USING #.#IIIIIIIIIIIIj";T3-T2P#
PRN3# = (T3#-OT3#/DELT
OT3#=T3#
PRINT "TPN3 u;USING".JJJJIIIJJJJIIIIIIJ";TPN3;
V#=(DTU#-ODTU#)/DELT#
ODTU#=DTU#
T2R#=(DWT#+DTU#+DUT#+DTW#)/C#
VR#=(T2R#-OT2R#)*C#/(2.*DELT#)         'V RELATIVE TO GT
OT2R#=T2R#
PRINT "Vr=N;USING "33.333333";VR#
TF#=T2#-T1#:TR# = T3# - T2#
PRINT "t3-t1= ";USINGU#.######## tf = #.#w~## tr = #.#IIIIIIIIII#";T2R#,TF#,TR#;
PRINT n F - R = n;USING"##.11111111#1111##n;TF# - TR#
PRINT USING ~##ff##.##;!Y1t1~Yt#.##~;RUM##RTM
INPUT u CR TO CONTINUE~,ANS$
NEXT IT
GOTO100
FNn
```

Appendix D.
RXTE/TRMM Software PDL

Appendix D.

/***
Prolog
TCK_USCCS_calc_t1t3
- This function will calculate the t1t3 pair for each sample collected. It will use the database constants to select the appropriate forward and return PN epochs.
- It will interpolate between points received in OPM66, since points are only on 1-second intervals to reduce the volume of data.
- It will use the data base constants TCK_PN_select and TCK_PN_PRESENT to select the t1 and t3 epochs.

Change History	Author	Change Summary
9/21/94	W. Conaway/V.Sank FH&A	Original Version

****
                                        PDL

Examine data from first APID-1
Select VCDU
current_frame_num= frame_num;
sc_time=utcf+sc_met;
current_sc_time=sc_time;
(IF) Assume sc_time within (n) ms of UTC *** n is a new db_constant****
go get t1,t3 and find t2
earliest_UTC_time_of_epoch=current_sc_time-n;
test to ensure not near (±2 sec of day rollover)
earliest_PB1_time=INT(earliest_UTC_time_of_epoch_
**** need only seconds of day***
FOR iloop=1,254 (using iloop +1 thus 254 not 255)
        if(earliest_PB1_time==ttm_repeat_array[iloop].ttm_opb1_time)
        break
NEXT
*** calculate fwd and rtn PN periods ***
ET_fwd_pn_periods=1+ttm_repeat_array[iloop+1.ttm_fwd_delta-
        ttm_repeat_array[iloop].ttm_fwd_delta;
ET_rtn_pn_periods=1+ttm_repeat_array[iloop+1].ttm_rtn_delta-
        ttm_repeat_array[iloop].ttm_rtn_delta;
fwd_pn_period=ET_fwd_pn_periods/12;
if(fwd_pn_period,.084)ET_fwd_pn_periods=/11;
if(fwd_pn_period,.086)status=PN_LENGTH_ERROR
ET_rtn_pn_periods=1+ttm_repeat_array[iloop+1].ttm_rtn_delta-
        ttm_repeat_array[iloop].ttm_rtn_delta;
rtn_pn_periods= ET_rtn_pn_periods/12;
if(rtn_pn_period,.084) rtn_pn_period=ET_rtn_pn_periods=/11;
if(rtn_pn_period,.086)status=PN_LENGTH_ERROR
Find time of 1st fwd and rtn epoch after 1 sec mark in units of UTC
first_t1'=PB1_time+ttm_repeat_array[iloop].ttm_fwd_delta;
first_t3'=PB1_time+ttm_repeat_array[iloop].ttm_rtn_delta;
find range time
put min_range_time .5 into editable file
irloop=0 ***initial value***

range_time=0 ***inital value***
WHILE (range_time,min_range_time)
　　　　t3'=first_t3'+irloop*rtn_pn_period;
　　　　range_time=t3'-first_t1';
　　　　irloop++;
END_while
earliest_t1'=earliest_UTC_time_of_epoch-range_time/2
now find actual T1 time
itloop=0
WHILE (range_time,min_range_time)
　　　　t3'=first_t3'+irloop*rtn_pn_period;
　　　　range_time=t3'-first_t1';
　　　　irloop++;
END_while
now get corresponding t3
t3'=t1'+range_time;
rtn_pm_epoch_time=t3'
Finally t2 can be calculated
t2_measured=9t1'+t3')/2+tlatch+(RSFfwd-RZSrtn)/2
<div align="center">PDL</div>
****

Appendix E. USCCS

(an example in simple terms)

USCCS (an example)

USCCS is designed to assist a spacecraft control center in the assessment and adjustment of their clock on board their spacecraft. The analytical considerations in section 4 are the mathematical background that supports the USCCS. Unless you are deeply involved with the design of the spacecraft or ground system, that mathematical treatise is totally dry and uninteresting. For the rest of us, USCCS can be explained in the following manner.

In the following example, the numbers are all fictitious but possible since all were based on CGRO and TDRS numbers. A simulation is included throughout this section.

As you should be aware by now, there is a clock flying on the spacecraft. There is also a clock on the ground in the ground terminal. From your own knowledge, it seems logical that both clocks would run together since, the clocks in your house all run together. On the surface, that is true but, the analog clocks in your house are all synchronized by the 60 Hz current that feeds them (key wound clocks excepted!). The clock in the spacecraft having no wires tying it to the earth has no alternative but to free run. The clock in the ground terminal is also free running, but is tied to a stable energy level transition in cesium atoms (Cesium Atomic Clock).

THEOREM: TWO FREE RUNNING CLOCKS NO MATTER HOW PRECISE NEVER RUN EXACTLY TOGETHER

The communications link that ties the spacecraft to earth (MA or SSA) has the capability of providing information sufficient to allow us to compute the difference in the two clocks "Time". There is a PN spreading code that is used on the TDRSS communications links, between the ground and the spacecraft that has a periodic pattern (18 ones) called the "EPOCH". This epoch recurs approximately every 85 msec. It is the recurrence of this epoch that is convenient for determining the difference between the two clocks.

As epochs leave the modulator in the ground terminal on their way to the spacecraft, the modulator reads the ground station cesium atomic clock. The signal with the epoch travels to the user spacecraft. Where the arriving epoch causes another similar epoch to travel with the communication signal back to the ground station. When the epoch is removed from the data signal in the ground receiver, the ground atomic clock is again read. By examining the two ground readings and realizing that the epoch was at the user spacecraft exactly half way in between, (to within a microsecond), we know when the epoch was at the user spacecraft. The data word contains the amount of time offset between the cesium generated 1-second time mark and the first epoch generated after that time mark (called T1).

The Epochs' Trip to the User

After the epoch has left the modulator, it travels to the antenna in the ground terminal and from there, on to the TDRS spacecraft. The time involved here is two fold, RZS_{fwd} and the range to TDRS. The time of signal flight to TDRS ($T_{GT-TDRS}$) can be computed as $range_{GT-TDRS}$ /speed of light. The epoch makes its way through TDRS and that time is defined as $TDRS_{FWDdelay}$. OPM-66 that is

supplied to the POCC combines RZS_{fwd} and $TDRS_{FWDdelay}$. The next part of the epoch's trip is the trip from TDRS to the user spacecraft. That time ($T_{TDRS-USER}$) again is $range_{TDRS-USER}$ /speed of light. The times $T_{GT-TDRS}$ and $T_{TDRS-USER}$ vary and this variation will be discussed a little later. Arrival of the epoch at the user spacecraft is defined as T2.

At the User

Once the epoch has reached the user, several things happen. After a short time, the user spacecraft clock is read (T_{user}). T2 is the time the reading was made on the spacecraft. The clock reading information is put into the telemetry stream for transmission to the ground. The delay between reading the clock and putting it into the telemetry stream is the responsibility of the user spacecraft C&DH designer to calculate measure and record for future use ($T_{userRDD}$).

The Epoch's Trip to the Ground

The epoch leaves the user spacecraft and travels to TDRS. That time ($T_{USER-TDRS}$) is the $range_{USER-TDRS}$ /speed of light. The epoch travels through TDRS ($TDRS_{RTNdelay}$). Finally, the epoch makes its way from TDRS to the ground terminal again, range/speed of light ($T_{TDRS-GT}$). The final portion of the journey is from the antenna to the integrated receiver (RZS_{RTN}) where the receiver outputs an offset time for the first epoch received after the first forward epoch after the one second time mark (called T3).

We've discussed the journey of the epoch from the modulator out through TDRS, the user Spacecraft and back through TDRS into the Integrated Receiver. While that was going on, the clock time that was read on board the user spacecraft was stuffed into the telemetry stream and headed to the ground. That telemetry stream after leaving the integrated receiver travels through the baseband switch and into the communications stream whether it is blocked in a Multiplexer/Demultiplexer (MDM) and then wrapped in a UDP packet structure.

Table 1 Static Data to Work With

Delay	Nsec	SEC	Range		
SC fwd	80	0.000000080	WSC-TDRS	40387	km
SC ret	246	0.000000246		0.134716512	sec
T user	142	0.000000142	TDRS-usr	38720.84813	km
Tuser RDD	117800	0.000117800		0.129159	sec
RZS fwd	700	0.000000700	speed of light	299792482.5	m/s
RZS SSA	800	0.000000800			
RZS MA	55500	0.000055500	TDRS Fwd S	250	0.000000250
	OPM-66		TDRS Fwd M	207	0.000000207
	TTM-1		TDRS Rtn S	308	0.000000308
PB-1 Time	xxxxxx4.000		TDRS Rtn M	1133	0.000001133
Fwd Dly	0.064912400	SEC	Transponder turnaround	325	0.000000325
Rtn Dly	0. 082205200	SEC	Epoch Calculation		
	TTM-2		Return	Forward	
PB-1 time	xxxxxx5.000		5.018172400	5.000911200	PB_1 time
Fwd Dly	0. 000911200	Sec	4.082205200	4.064912400	PB_1 time
Rtn Dly	0. 018172400	Sec	0.0850879272	0.085090800	PN period

It is that clock time that we are trying to verify and verify it we will. We will use the epochs that we have just followed from ground station to user and back. It was those epochs that caused the clock to be read and therefore it is those epochs that will enable us to correlate the clock. Table 1 lists all the constants we will utilize in computing the time on board the user spacecraft.

Table 2 S/C Clock time

4.669152232

Table 2 gives us the spacecraft clock time sample that was contained in the telemetry. Note that this is not necessarily utilizing the first epoch after the time hack but we can and will figure that out later.

Round Trip Time and Other Wonderful Things.

Now I'll bet you are wondering how we could use the offset time from the one second time mark to the forward epoch (T1) and the return epoch (T3) to calculate anything. Remember that periodic (85 msec) epoch? Well, periodic means that it has a regular period. Armed with that knowledge and the offset from the one second time mark, we can seemingly recreate epochs ad infinitum. In reality, there are one second time marks every second and an accompanying T1 offset time. With two time marks and the attendant offsets, we can compute the actual period of the epoch between the two time marks. If you remember, when we introduced the epoch, we said the period was approximately 85 msec. The reality is that with the precise forward frequency of 2106.406250 MHz., the period is 0.08508936394 seconds. The

forward frequency is fixed at 2106.406250 MHz. under Doppler Compensation Inhibit conditions. The rest of the time, frequency and thus the period are varied slightly by the anticipated velocity and the oscillator error of the user spacecraft. For the purposes of our calculation, it is safe to assume that the epoch period is 85 msec. plus or minus 1 msec. Taking the second offset of the forward epoch plus the time mark base second and subtracting the previous time mark base second and then adding the offset of the associated forward epoch, then dividing by eleven or twelve will render the real period of the epoch. Referring to table 3 we can see sample delay times reported in the OPM-66.

Table 3 OPM 66 extracted. Note that each Time Transfer Message (TTM) has both Fwd and Rtn delays as well as a PB-1 time. For simulation purposes, only the whole second portion of the PB-1 time is shown. Fwd Dly is the offset from the time mark to the forward PN epoch which we earlier called T1. Using the Fwd Dly from Entry 2, we can recreate the time of the first epoch in second 5 as 5.000911200. We recreate the first epoch in second 4 using Entry 1 in a similar manner getting 4.064912400.

Table 3 OPM 66 extracted.

	OPM-66	
	TTM-1 Entry 1	
PB-1 Time	xxxxxx4.000	
Fwd Dly	0.064912400	SEC
Rtn Dly	0.082205200	SEC
	TTM-2 Entry 2	
PB-1 time	xxxxxx5.000	

Fwd Dly	0.000911200	Sec
Rtn Dly	0.018172400	Sec

Taking the difference of the two gives us 0.9359988 seconds. Taking this number and dividing by 11 gives a period of 0.0850908, which must be correct since we know that the epoch must be about 85 msec. We now know that 11 epoch's periods elapsed between the measured epochs. We can similarly recreate the T3 epoch returns and end up with 5.018172400 and 4.082205200 as the two numbers with a difference of 0.9359672 seconds. Again calculating the period we divide by 11 (actually could be 11,12 or 13) and get a period of 0.085087927 seconds. Taking the numbers we just calculated for the epoch periods, we can recreate the epochs that occurred in that time period. The forward epochs are the easiest. Starting at second 4 and adding the FWD DLY time of 0.0649124 sec. gives us the time of the first epoch (T1). We repetitively add the epoch period we calculated for the forward epochs to the first epoch time and record the resultant times. We now have a picture of the epochs that were in motion during the interval between second #4 and second #5 around the time that the spacecraft clock was read and inserted into the telemetry stream. Repeat the process for the return epochs.

Table 4 Epochs

	FWD Epochs	RTN Epochs
T1/T3	4.064912400	4.082205200
epoch	4.150003200	4.167293127
epoch	4.235094000	4.252381055
epoch	4.320184800	4.337468982
epoch	4.405275600	4.422556909
epoch	4.490366400	4.507644836

epoch	4.575457200	4.592732764
epoch	4.660548000	4.677820691
epoch	4.745638800	4.762908618
epoch	4.830729600	4.847996546
epoch	4.915820400	4.933084473
T1/T3	5.000911200	5.018172400
	T1s	**T3s**

We can now utilize that information to find which specific epoch caused the clock to be read. Due to the geometry of a satellites orbit and the TDRS orbit, we know that the round trip time for an epoch is greater than 0.5 seconds but never greater than 0.585 seconds. Logically the one way time would then be .25 to .293 seconds. For the moment, I ask that you accept those numbers without proof. Referring back to table 2, the spacecraft time tag was 4.669152232. If we subtract 0.25 seconds from that time tag, and examine the epochs in table 4 we seek the T1 which precedes the calculated time (4.41952232). The T1 epoch that fits the description occurred at 4.405275600 seconds. That epoch is the one that caused the clock to be read but that doesn't give us the time offset. We need to compute the range of the spacecraft. Taking the T1 epoch and adding the minimum range time of 0.5 seconds gives us the earliest time that T3 could have occurred (4.9052756). The closest T3 is 4.933084473 sec. A precise measure of round trip range is the difference between t3 and t1 or 4.933084473 - 4.405275600 = 0.527808873sec. Consider for a second that the rough range includes all of the delays we have enumerated. That means that the real range is less than we have calculated. All of the delays include the RZS_{fwd}, RZS_{rtn}, $TDRS_{fwd}$, $TDRS_{rtn}$, $User_{fwd}$, $User_{rtn}$ and turnaround delay. The sum total of all of these in the configuration we have been using amount to 2709 nsec. Taking

that sum from the rough range, we have a range free of delays. That range is now 0.527806164 sec. Until now, we haven't mentioned the service mode, which we will assume as Multiple Access. To get the actual T2 time on the spacecraft, we need to apply the USCCS algorithm, which says first

- T2 is the average of T1 and T3. T2 = 4.405275600 + 4.933084473 / 2 = **4.669180036**

- Plus 1/2 the difference in the ground terminal RZS delays. T2= 4.669180036+ (0.000000700- 0.000055500)/2 = **4.669152636**

- Plus 1/2 the difference in TDRS delays. T2 = **4.669152636**+ (0.000000207 - 0.000001133)/ 2= **4.669152173**

- Plus 1/2 the difference in User S/C delays. T2 = **4.669152173**+ (0.000000080 - 0.000000246)/2= **4.669152090**

- Plus T_{user}. T2= **4.669152090**+ 0.000000142 = **4.669152232**

This T2 is the actual time that the clock on the spacecraft was latched for transmission to the ground. The clock error is the difference of that time and the clock reading at that time which was 4.669152232. The difference is 0.000000000 sec. If you remember when we set out, we knew nothing about the clock or its accuracy. The calculation we just made accounted for everything except the difference in transit time between forward and return range, which is less than 1 microsecond.

Note as we said earlier, this was a simulation and the numbers really do add up correctly. In actuality, the numbers may not add up quite that nicely but they will be very close.

NASA Time Codes

PB TIME

	flag											
PB-1		2^8	9 Bits Day of Year	2^0	2^{26}	27 Bits Milliseconds of day	2^0					
PB1-A		2^8	9 Bits Day of Year	2^0	2^{36}	37 Bits Microseconds of day	2^0					
PB1-B		2^8	9 Bits Day of Year	2^0	2^{46}	47 Bits Nanoseconds of day	2^0					
PB2		2^8	9 Bits Day of Year	2^0	2^{36}	37 Bits Milliseconds of day	2^0					
PB3		2^8	9 Bits Day of Year	2^0	2^{16}	17 Bits Seconds of day	2^0	2^9	10 Bits ms	2^0	2^9	10 B
PB3-A		2^8	9 Bits Day of Year	2^0	2^{16}	17 Bits Seconds of day	2^0	2^9	10 Bits ms	2^0	2^9	10 B
PB4		2^8	9 Bits Day of Year	2^0	2^{26}	27 Bits Milliseconds of day	2^0	2^9	10 Bits us	2^0		
PB4-A		2^8	9 Bits Day of Year	2^0	2^{26}	27 Bits Milliseconds of day	2^0	2^9	10 Bits us	2^0	2^9	10 B
PB5		2^{13}	14 Bits TJD	2^0	2^{16}	17 Bits Seconds of day	2^0	2^9	10 Bits ms	2^0	2^9	10 B
PB5-A	0	2^{13}	14 Bits TJD	2^0	2^{16}	17 Bits Seconds of day	2^0					
PB5-B	1	2^{13}	14 Bits TJD	2^0	2^{16}	17 Bits Seconds of day	2^0	2^9	10 Bits ms	2^0		
PB5-C	1	2^{13}	14 Bits TJD	2^0	2^{16}	17 Bits Seconds of day	2^0	2^9	10 Bits ms	2^0	2^9	10 Bi
PB5-D	1	2^{13}	14 Bits TJD	2^0	2^{16}	17 Bits Seconds of day	2^0	2^9	10 Bits ms	2^0	2^9	10 Bi

IRIG

	flag											
IRIG-A	0	2^{13}	14 Binary TJD	2^0	2^{16}	17 Binary Seconds of day	2^0					
IRIG-B	1	2^{13}	14 Binary TJD	2^0	2^{16}	17 Binary Seconds of day	2^0	2^9 10 Binary ms	2^0			
IRIG-C	1	2^{13}	14 Binary TJD	2^0	2^{16}	17 Binary Seconds of day	2^0	2^9 10 Binary ms	2^0	2^9	10 Bi	
IRIG-D	1	2^{13}	14 Binary TJD	2^0	2^{16}	17 Binary Seconds of day	2^0	2^9 10 Binary ms	2^0	2^9	10 Bi	

CCSDS Binary

CCSDS	2^{31}	32 Bits Binary	2^0	Microseconds since 00:00 GMT, 1 January 1970 Modulo 2^{32}

Note: This format doesn't work, but is included for completeness

To make this format usable, redefine it to Seconds since 00:00 GMT, 1 January 1970 Modulo 2^{32}

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